Lunar Surface Systems Concept Study

Innovative Low Reaction Force Approaches to Lunar Regolith Moving

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About Honeybee

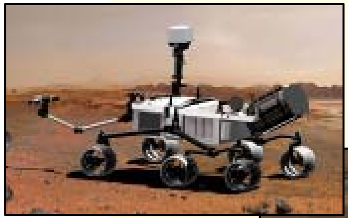
ISO 9001
AS9100
Certified

- **Honeybee Robotics** Spacecraft Mechanisms Corp.
  - Est. 1983
  - HQ in Manhattan, Field office in Houston
  - ~50 employees
  - ISO-9001 & AS9100 Certified
- **End-to-End capabilities:**
  - Design:
    - System Engineering & Design Control
    - Mechanical & Electrical & Software Engineering
  - Production:
    - Piece-Part Fabrication & Inspection
    - Assembly & Test
  - Post-Delivery Support:
- **Facilities:**
  - Fabrication
  - Inspection
  - Assembly (Class 10 000 clean rooms)
  - Test (Various vacuum chambers)
- **Subsurface Access & Sampling:**
  - Drilling and Sampling (from mm to m depths)
  - Geotechnical systems
  - Mining and Excavation



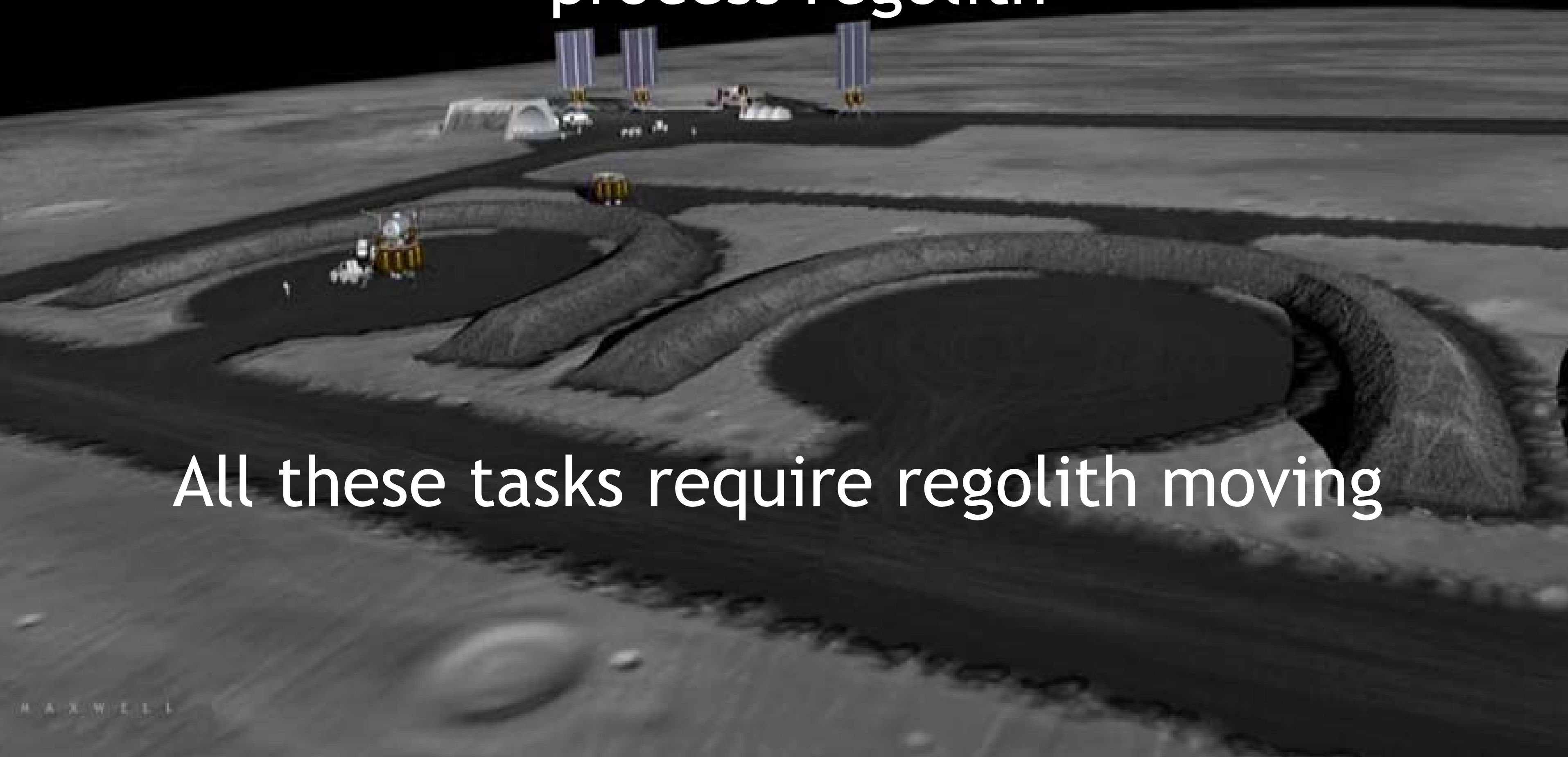






We are going back to the Moon to stay

We need to build homes, roads, and plants to process regolith



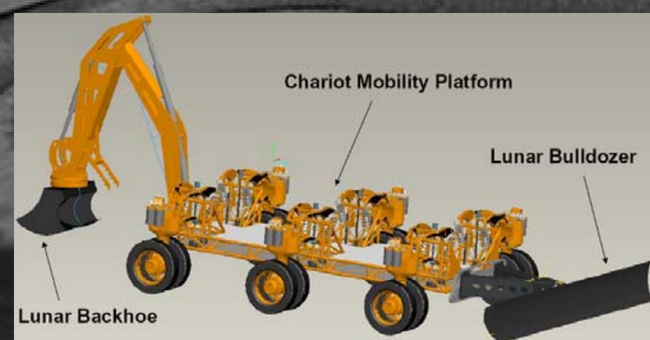
All these tasks require regolith moving

Excavation Requirements*

All excavation tasks can be divided into two:

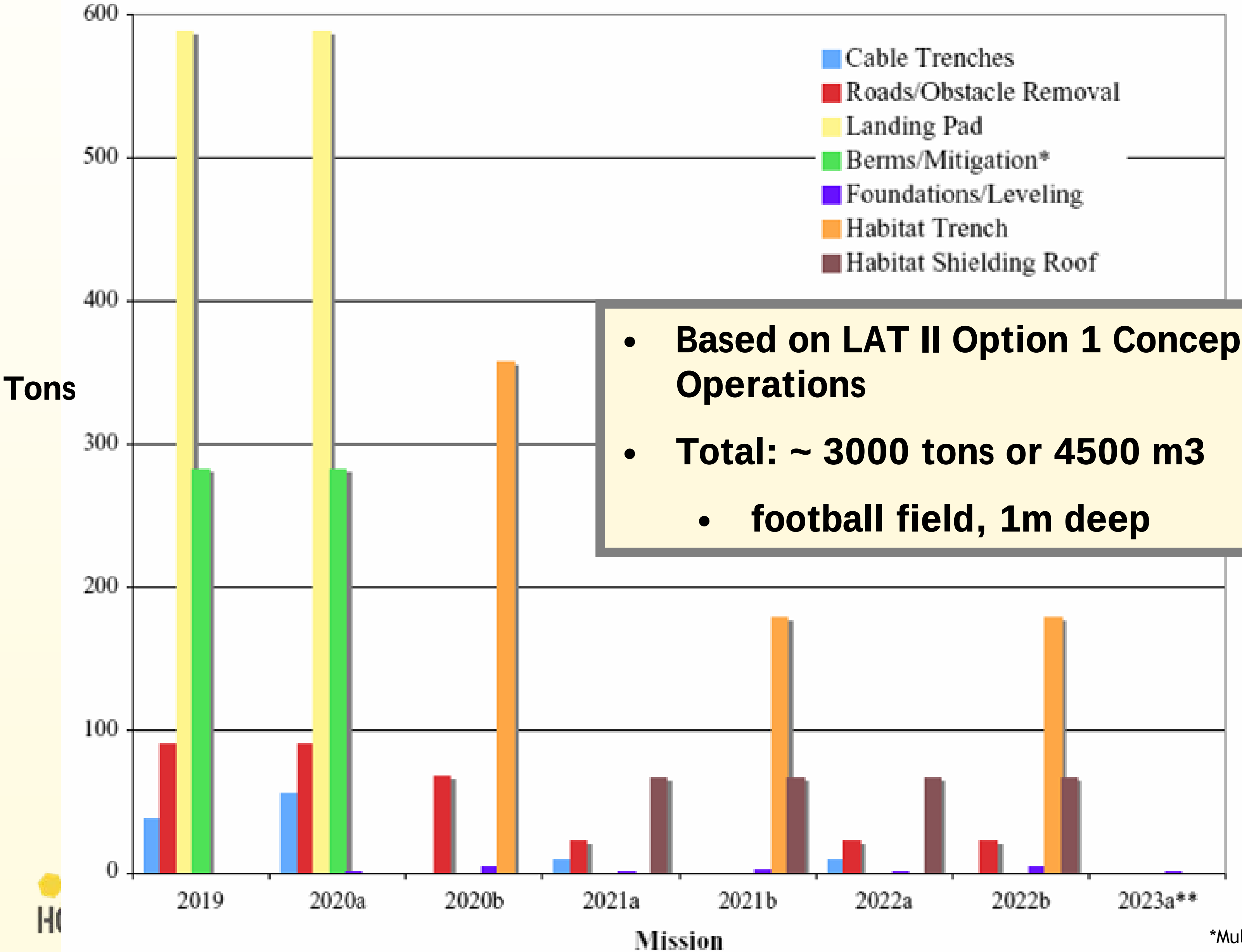
1. Digging
   - Electrical Cable Trenches
   - Trenches for Habitat
   - Element Burial
   - ISRU (O2 Production)

2. Plowing/Bulldozing
   - Landing / Launch Pads
   - Blast Protection Berms
   - Utility Roads
   - Foundations / Leveling
   - Regolith Shielding



*Muller and King, STAIF 08

Excavation Requirements*



- Based on LAT II Option 1 Concept of Operations
- Total: ~ 3000 tons or 4500 m3
  - football field, 1m deep

*Muller and King, STAIF 2008

How big excavator do we need?

Bottom-Up Approach to Lunar Excavation

- The excavator mass and power requirements are driven by excavation forces
- Excavation forces are function of:
  - Independent parameters (fixed):
    - soil cohesion, friction angle, and gravity
  - Excavator parameters (variable):
    - depth of cut, scoop design etc.
- In order to 'size' a lunar excavator need to follow the following steps…

1. Choose a soil:

JSC-1a, GRC1, NU-LHT-1M..

↓

2. Prepare the soil:

- Relative Density, Dr = 0% - 100%
- Penetration Resistance

↓

3. Measure Excavation Forces

↓

4. Scale forces for lunar G

↓

5. Input into excavation models

1. Choose a soil:

JSC-1a, GRC1, NU-LHT-1M..

2. Prepare the soil:

- Relative Density, Dr = 0% - 100%
- Penetration Resistance

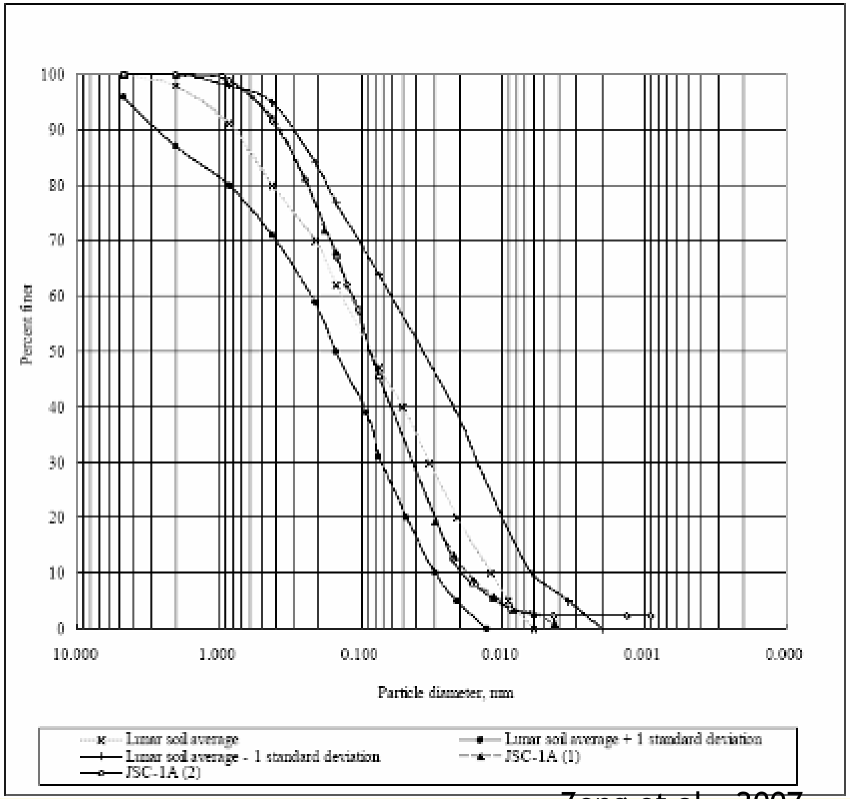
3. Measure Excavation Forces

4. Scale forces for lunar G

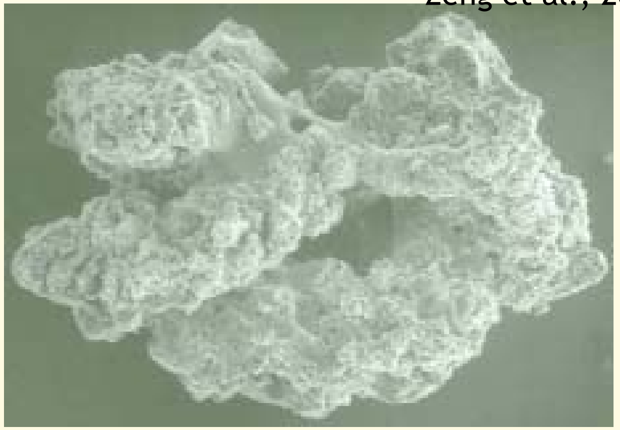
5. Input into excavation models

1. Properties of Lunar soil

- Lunar Regolith
  - Highly compacted soil (silty sand)
  - High Cohesion: 1kPa
  - High Friction Angle: 45-50 deg
  - Agglutinates
  - Very abrasive
- Effect of Hard Vacuum: 10^{-12} torr
  - Surface friction is high -> soils are stronger



Zeng et al., 2007

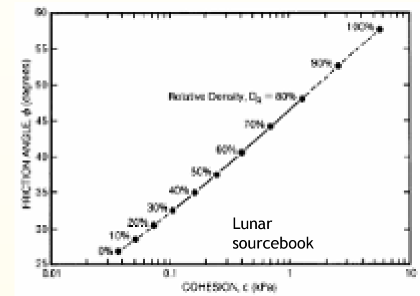


Courtesy: D. McKay

HONEYBEE ROBOTICS

1. Requirements for Lunar Soil Simulant

- Simulants do not replace. They simulate specific property/properties and not necessarily all the properties (mechanical for digging vs. mineral composition for Oxygen extraction): “Horses for courses”
- What soil properties are important for lunar excavation?
  - Friction angle (φ) and Cohesion (c): $\tau = \sigma \tan(\varphi) + c$
    - However, φ and c are function of soil relative density
      - Which in turn is affected by particle size distribution and particles shape, (and mineralogy)



Available soil simulants

Simulant	Type	Primary use	Manufacturer
JSC-1a	Mare, low-Ti	Geotechnical and to lesser chemical	Orbitec
NU-LHT-1M, -2M	Highlands	General	MSFC and USGS
OB-1	Highlands	Geotechnical	Norcat
FJS-1	Mare, low-Ti	Geotechnical	JAXA/Schimizu
GRC-1, 3		Geotechnical	GRC

Selected:

1. **Good properties**
2. **Availability**

JSC-1a

1. Choose a soil:

JSC-1a, GRC1, NU-LHT-1M..

2. Prepare the soil:

- Relative Density, Dr = 0% - 100%
- Penetration Resistance

3. Measure Excavation Forces

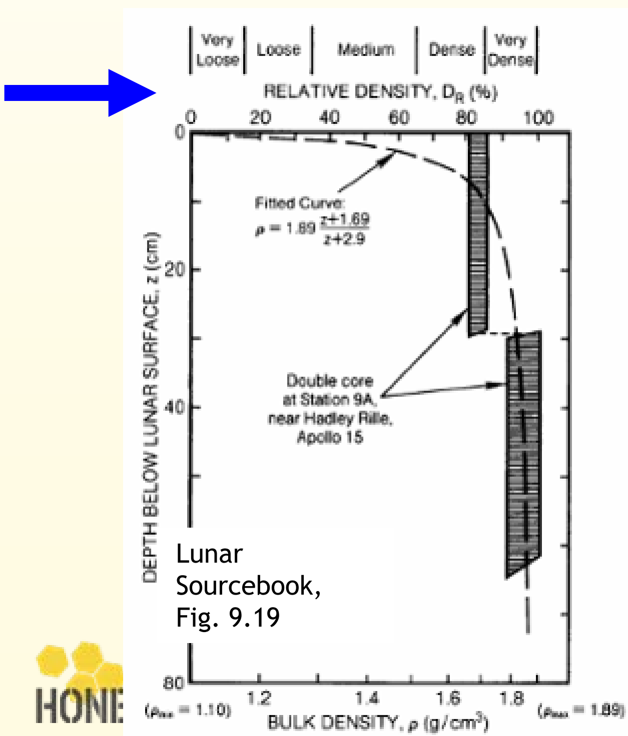
4. Scale forces for lunar G

5. Input into excavation models

2. Soil Preparation Requirements

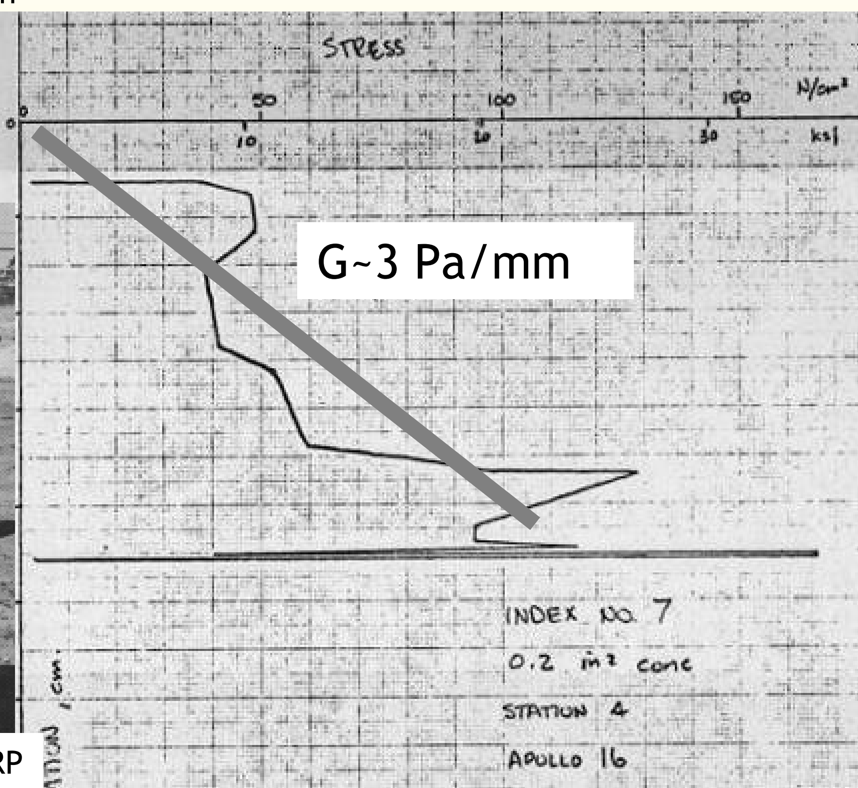
There are two parameters that can guide soil preparation:

1. Relative density, Dr
   - Compact the soil to achieve Dr to that on the Moon, [0-100%]
   - Can assume worst case, Dr ~90%
2. Penetration resistance gradient, G [Pa/mm]
   - Compact the soil to match the penetration resistance gradient of the Apollo SRP
   - Need gravity scaling factor, $G_{Earth}=k * G_{Moon}$, where k= 1 to 6



Lunar Sourcebook, Fig. 9.19

Apollo SRP



2. Soil Preparation: Conclusions

It is recommended that soil simulant is compacted to achieve Dr>90%, which is consistent with depth below ~10-20 cm. This creates worst case scenario and makes excavation results conservative.

This approach was also recommended by Dr. David Carrier

1. Choose a soil:

JSC-1a, GRC1, NU-LHT-1M..

JSC-1a

2. Prepare the soil:

- Relative Density, Dr = 0% - 100%
- Penetration Resistance

Dr~90%

3. Measure Excavation Forces

4. Scale forces for lunar G

5. Use these for excavation models

3. Measure Excavation Forces

- No published data exists giving bulldozer or digging forces in lunar regolith simulant
- Thus:
  - Theoretical models were used to predict the forces
  - The same models were used to determine gravity scaling

1. Choose a soil:

JSC-1a, GRC1, NU-LHT-1M..

2. Prepare the soil:

- Relative Density, Dr = 0% - 100%
- Penetration Resistance

3. Measure Excavation Forces

4. Scale forces for lunar G

5. Use these for excavation models

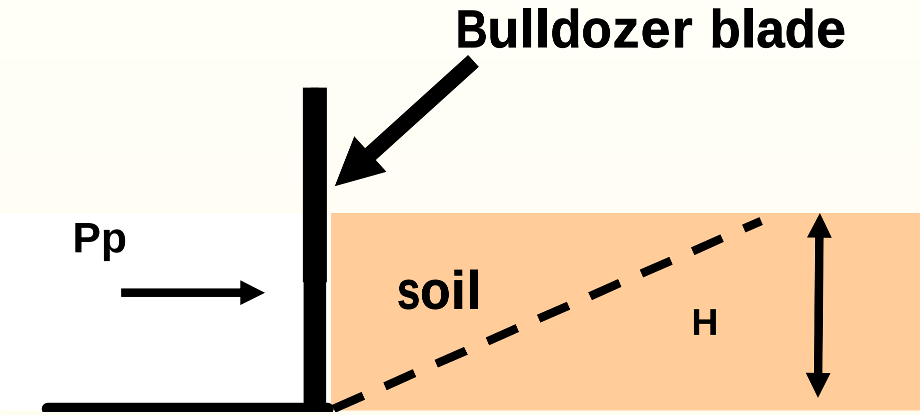
3 & 4. Forces and Gravity scaling: simple model

Force required to push the soil:

$$P_p = 0.5*\rho*g *H^2*N_\Phi + 2*c*H*N_\Phi^{0.5}$$

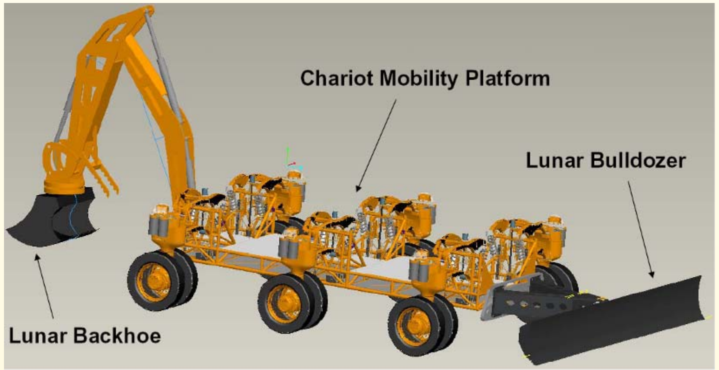
where:

$N_\Phi = [1+\sin\Phi]/[1-\sin\Phi]$



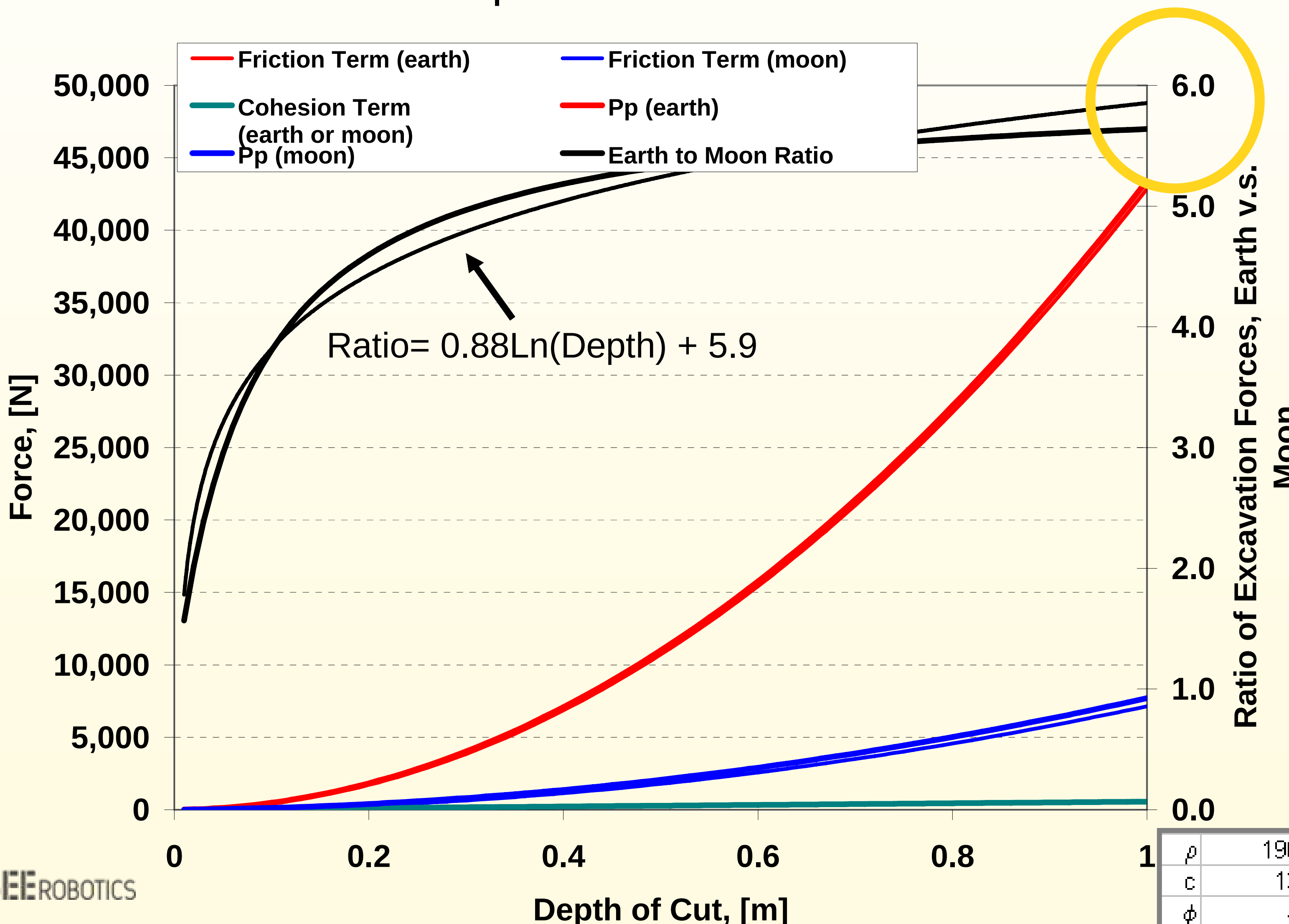
Note:

- Friction term [$Pp=0.5*\rho*g *H^2*N_\Phi$] has gravity component
- Cohesion term [$2*c*H*N_\Phi^{0.5}$] does not have a gravity component
- Next two charts show the effect of low and high cohesion



3 & 4. Low cohesion case; c=130 Pa

For low cohesion values, the gravity scaling factor reaches 6 for the blade depth of 1m into the soil



ρ	1900	kg/m3
c	130	N/m2
ϕ	40	degrees

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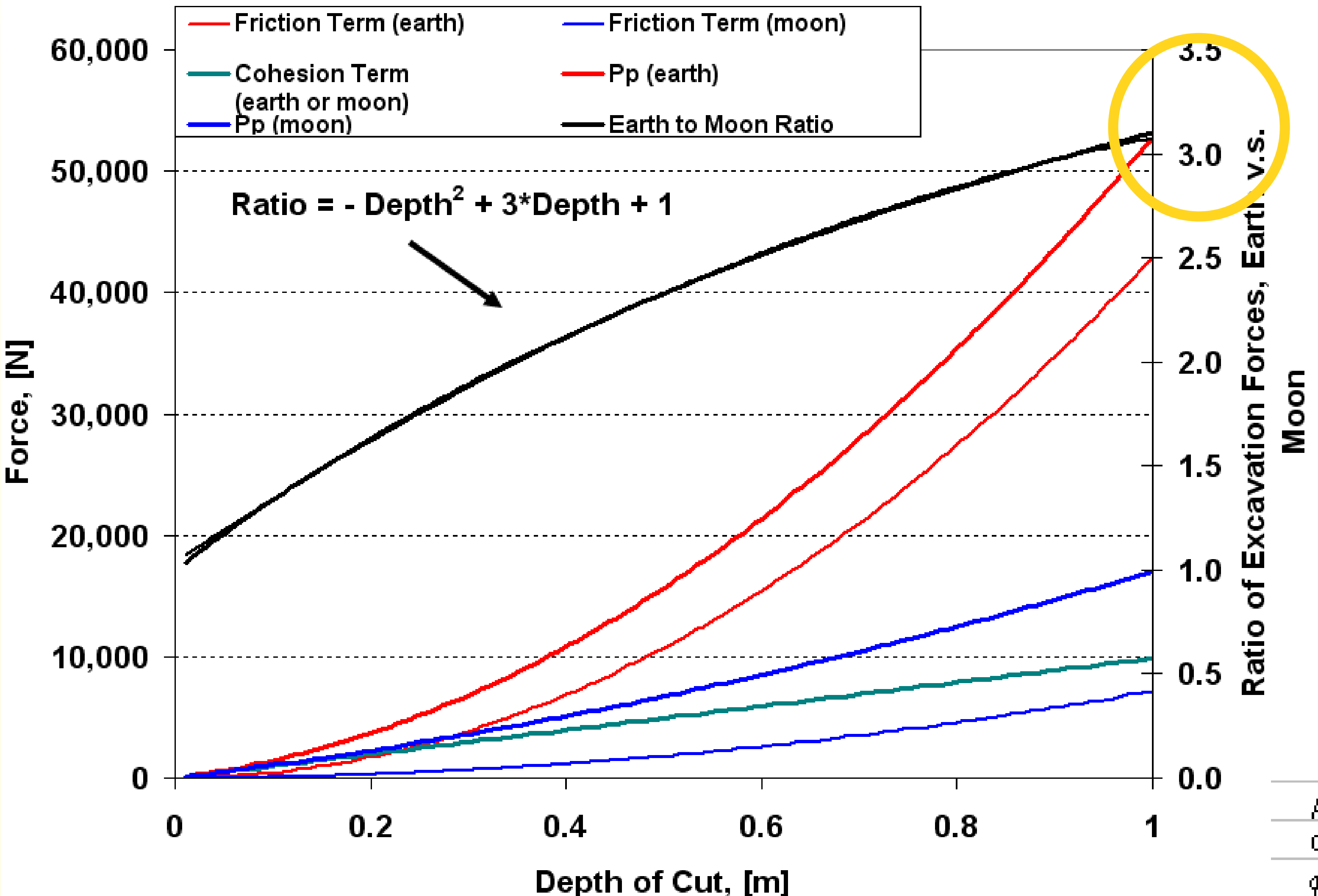
3 & 4. High cohesion case; c=2300 Pa

For high cohesion values, the gravity scaling factor reaches only 3 for the blade depth of 1m into the soil



ρ	1900	kg/m3
c	2300	N/m2
ϕ	40	degrees

3 & 4. Force and Gravity scaling: Zeng model*

- Zeng model takes into account more soil/blade parameters
- The model also predicts the gravity scaling as a function of blade depth into the soil
- A little bit of cohesion makes a big difference, especially in low gravity.

	Exacation forces at		
c=130 N/m2	g=9.8 m/s2 N	g=1.6 m/s2 N	Ratio
Depth=0.1m	1061	242	4.4
Depth=0.5m	27653	5119	5.4
Depth=1m	122428	21870	5.6
	Exacation forces at		
c=1300 N/m2	g=9.8 m/s2 N	g=1.6 m/s2 N	Ratio
Depth=0.1m	1785	964	1.9
Depth=0.5m	33231	10643	3.1
Depth=1m	138604	37790	3.7

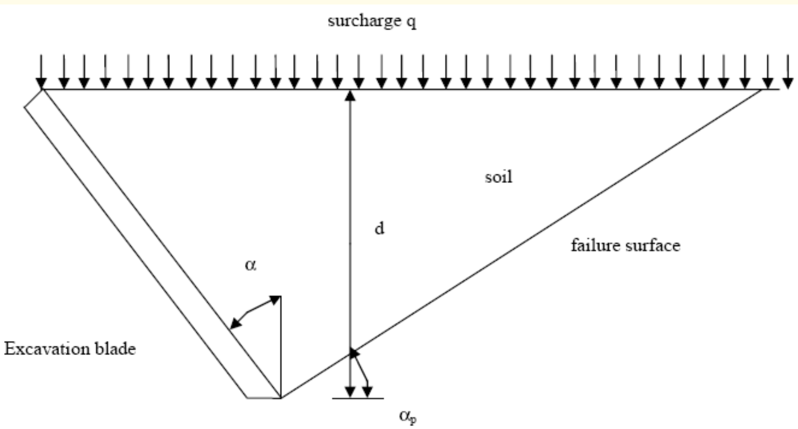


Figure 3. Excavation blade and soil body at failure

* X. Zeng et al., "Calculation of Excavation Force for ISRU on Lunar Surface," AIAA, 2007

Why excavator mass is important

The excavator has to provide resistance to the digging forces

- **If vertical forces are too high -> excavator will lift itself up and slip**
- **If horizontal forces are too high -> excavator will pull itself along**

The ideal tractive thrust :

$$H_0 = nbLc + W \tan \phi.$$

Note: Fully loaded Apollo rover (700 kg): 239 N*

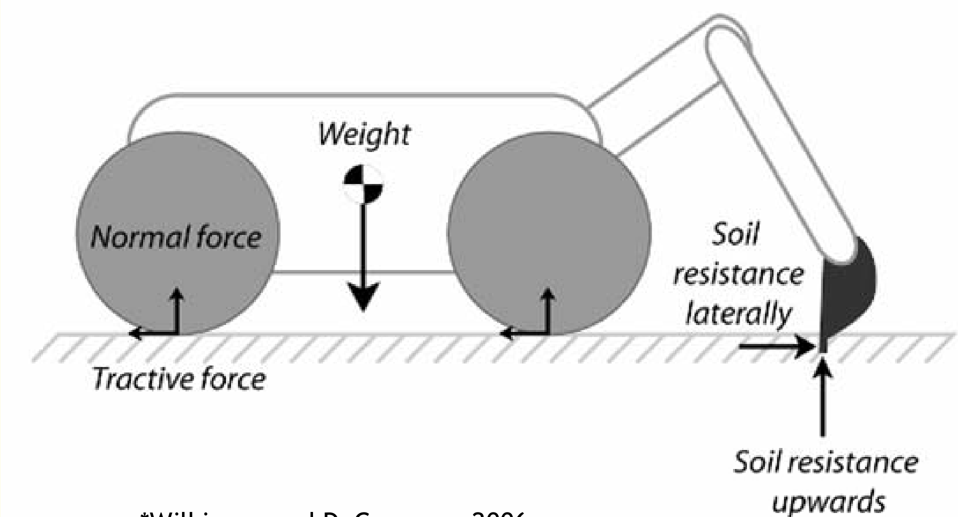
where:

[can not change these]

- C=soil cohesion
- phi=soil internal friction angle

[can change these]

- W= vehicle mass
- N=number of wheels
- B=width of a wheel
- L=wheel contact length



*Wilkinson and DeGennaro, 2006

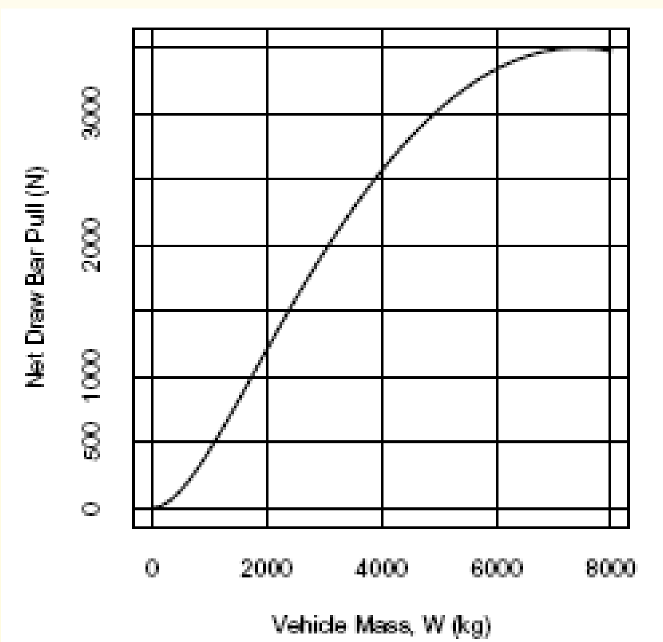
Traction model*

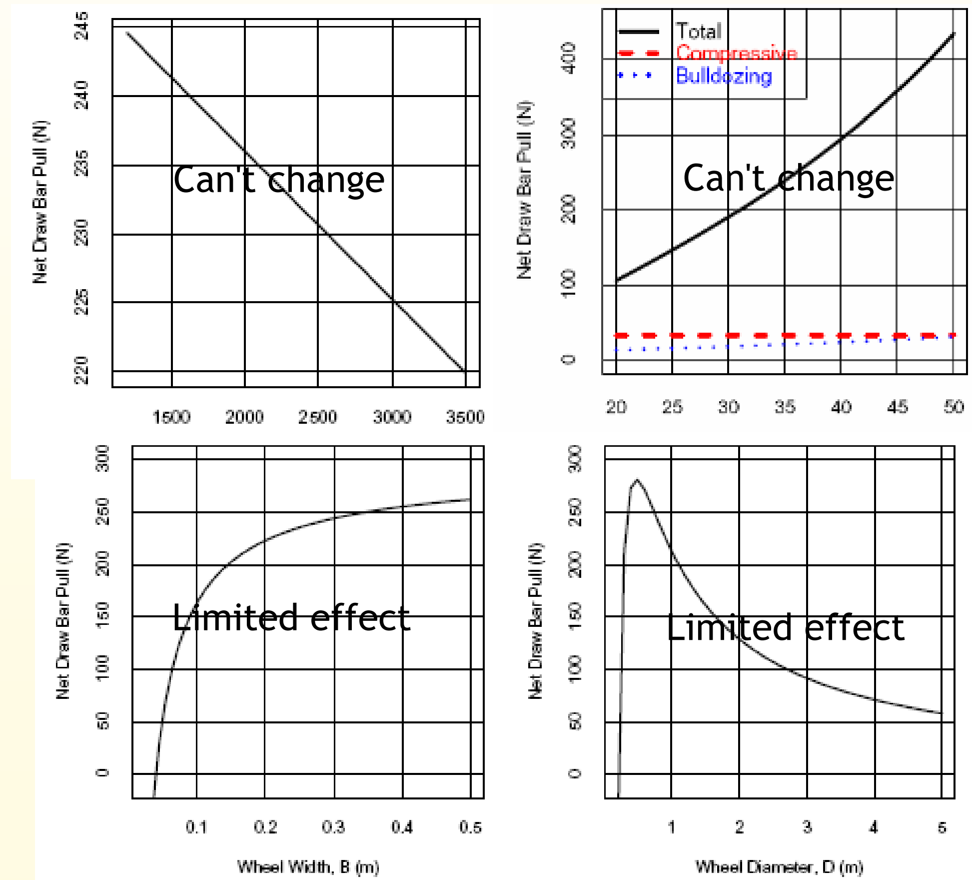
Actual DrawBar Pull = traction force – resistances (sinkage, bulldozing, hill climbing):

$$DP = H - R = H - (R_c + R_b + R_g + R_{other})$$

Bottom line:

Vehicle Mass has the biggest effect!

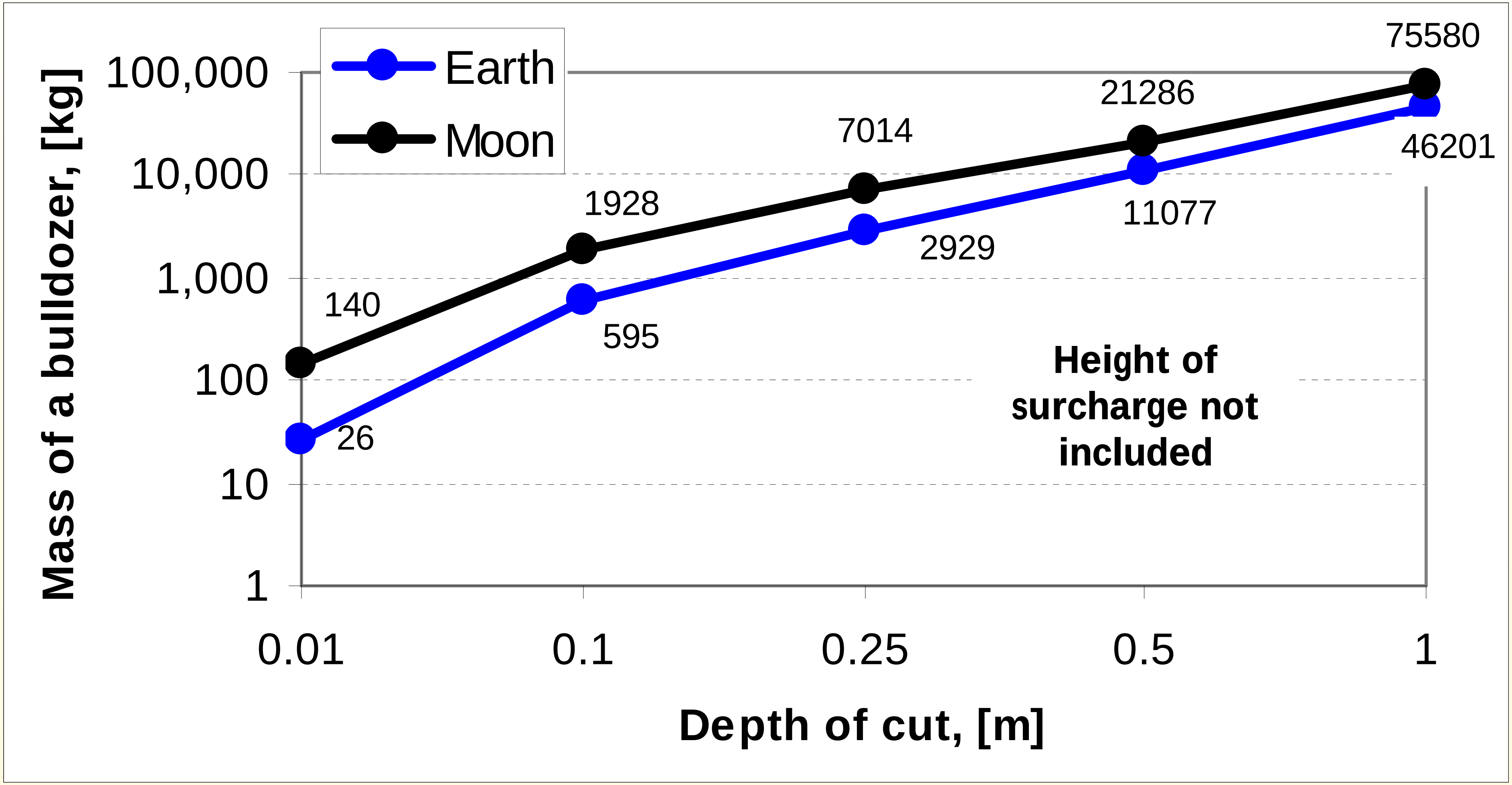




*Wilkinson and DeGennaro, 2006

3 & 4. Excavator Mass

Bulldozer cutting up to 10cm deep needs to weigh 2000 kg*



*Assumed: Vehicle Mass= 3 * Drawbar pull

Based on Zeng model.

Density=1.9 g/cc; Friction angle: 40 deg; Cohesion: 1300 Pa; Blade width: 1m

3 & 4. Conclusions

1. Need very heavy excavators
2. The excavation forces on Earth will be 1 - 6 times as great as on the Moon:

- ~1 for 'tiny' excavators
  - Thus need 6x more massive excavator
- ~2 for a "typical" excavator
  - Thus need 3x more massive excavator
- ~6 for a big excavator
  - The excavator mass may remain the same

Earth **Moon**

Depth = 0.25 m

2929 kg*

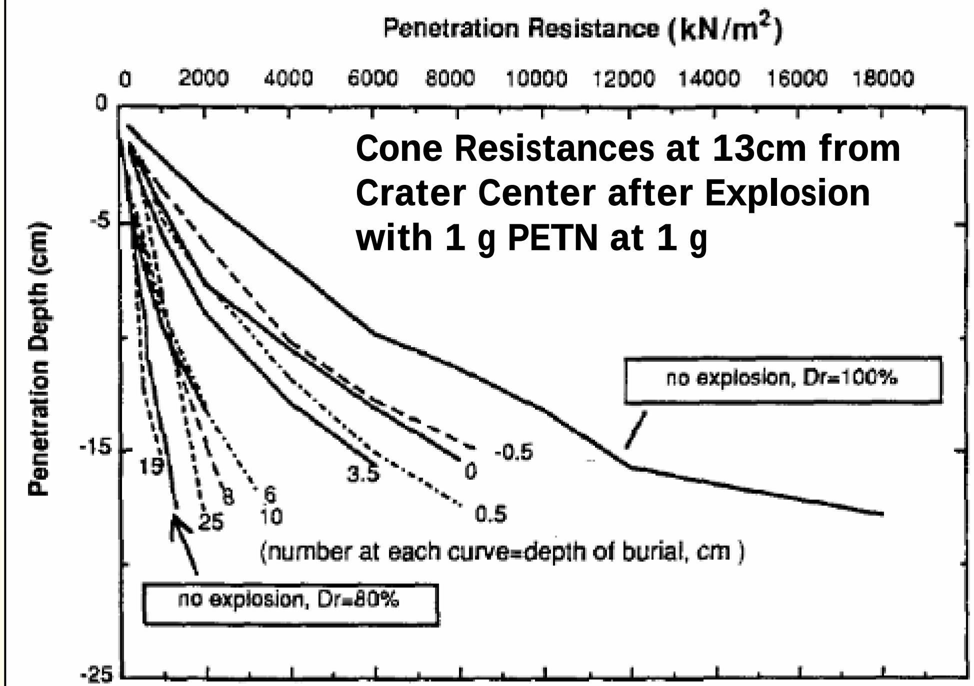
7014 kg*

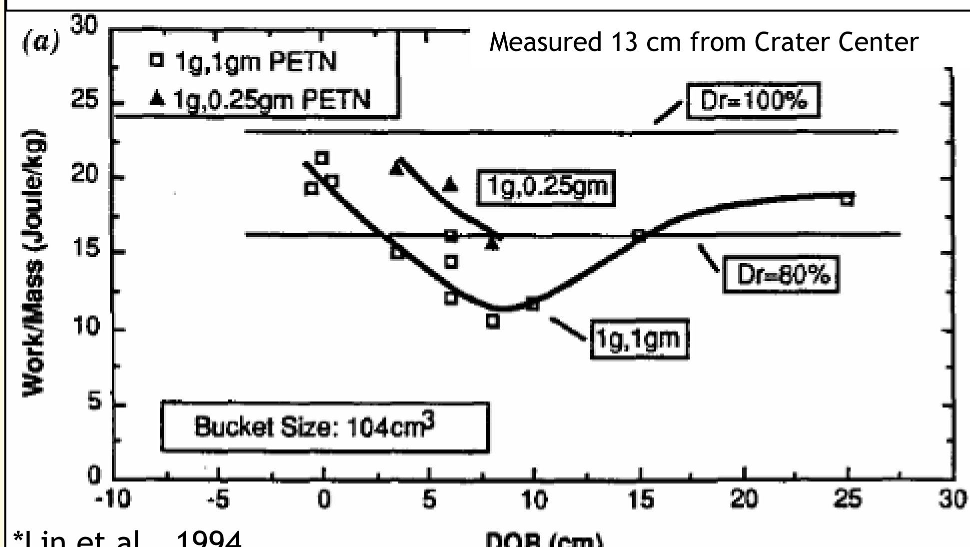
HONEYBEE ROBOTICS

To make regolith moving on the Moon feasible we need to find means of reducing excavation forces and in turn excavator mass

Use of explosive to loosen soil*, (1994)

- Experimental data: mass of explosives required for reduction in soil relative density (Dr) and excavation energy:
  - 1gram PETN->50% energy reduction
- Charges can be placed by:
  - Drilling detachable bit/explosive
  - Hammering detachable cone/explosive
- “Blasting” could be accomplished with gas pulse

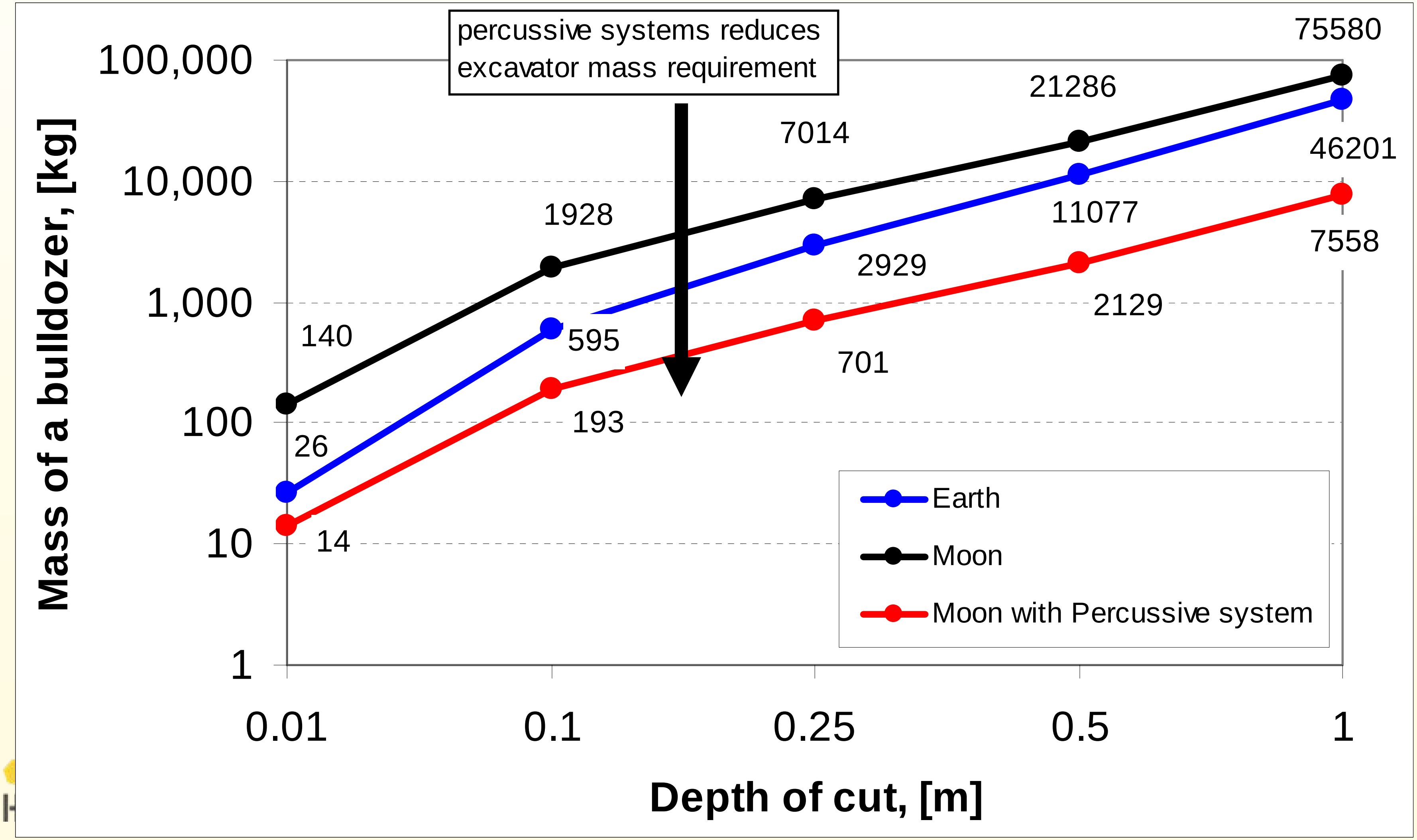




*Lin et al., 1994

Use percussive scoop/blade

- Force reduction ~ 90%
- Draft $Force_{vibratory}$=0.9 Draft $Force_{static}$



If excavation forces are reduced by 90%, the required vehicle mass will also be reduced by 90%.

But, the payback is much higher!!!

Smaller excavator means:

- smaller lunar landing mass and propellant to land
- smaller launch mass and less propellant to launch

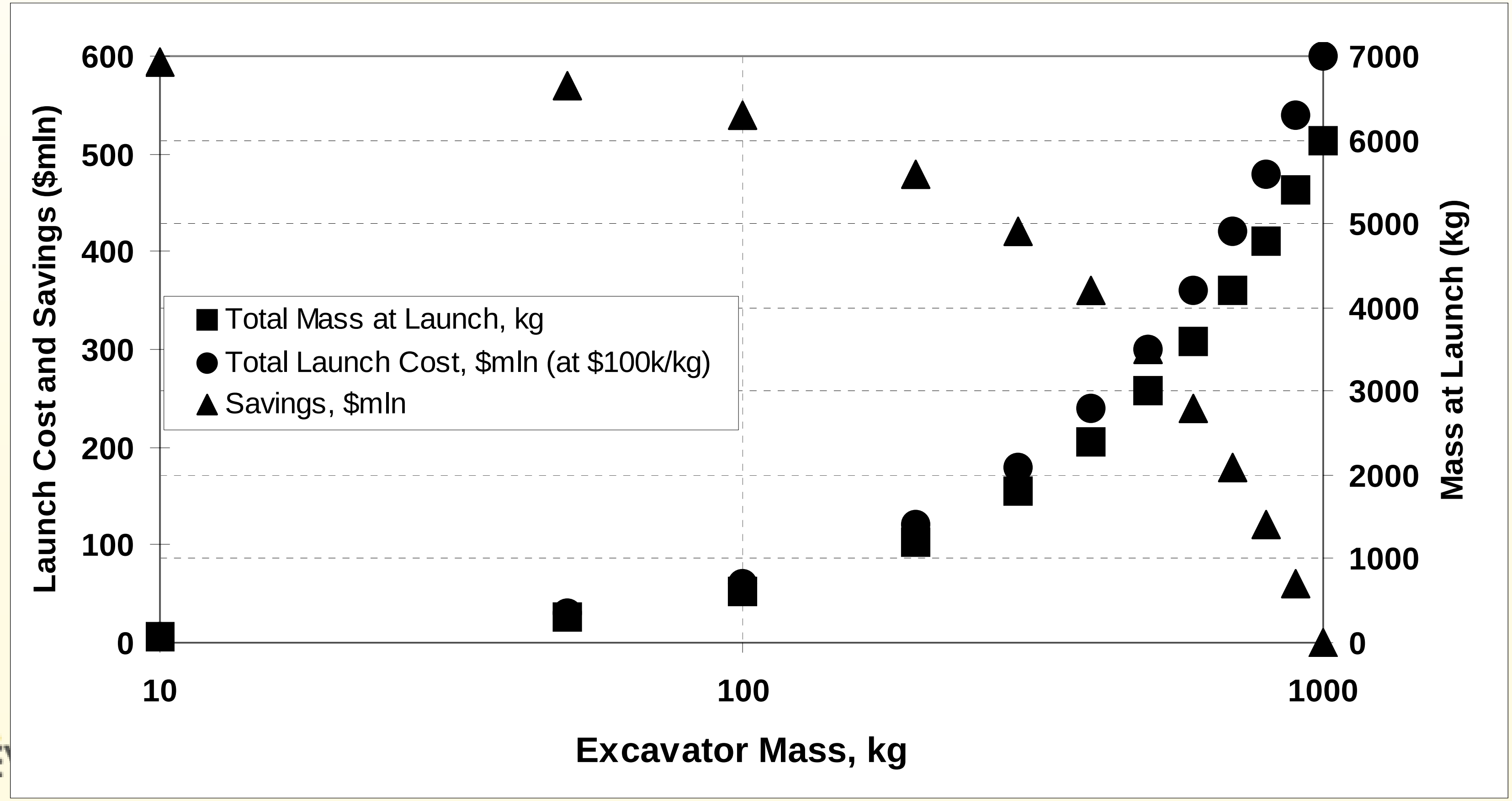
Payback for reduced excavation forces

Assumptions:

- Launch cost: $100k/kg
- Gear ratio: 1:6

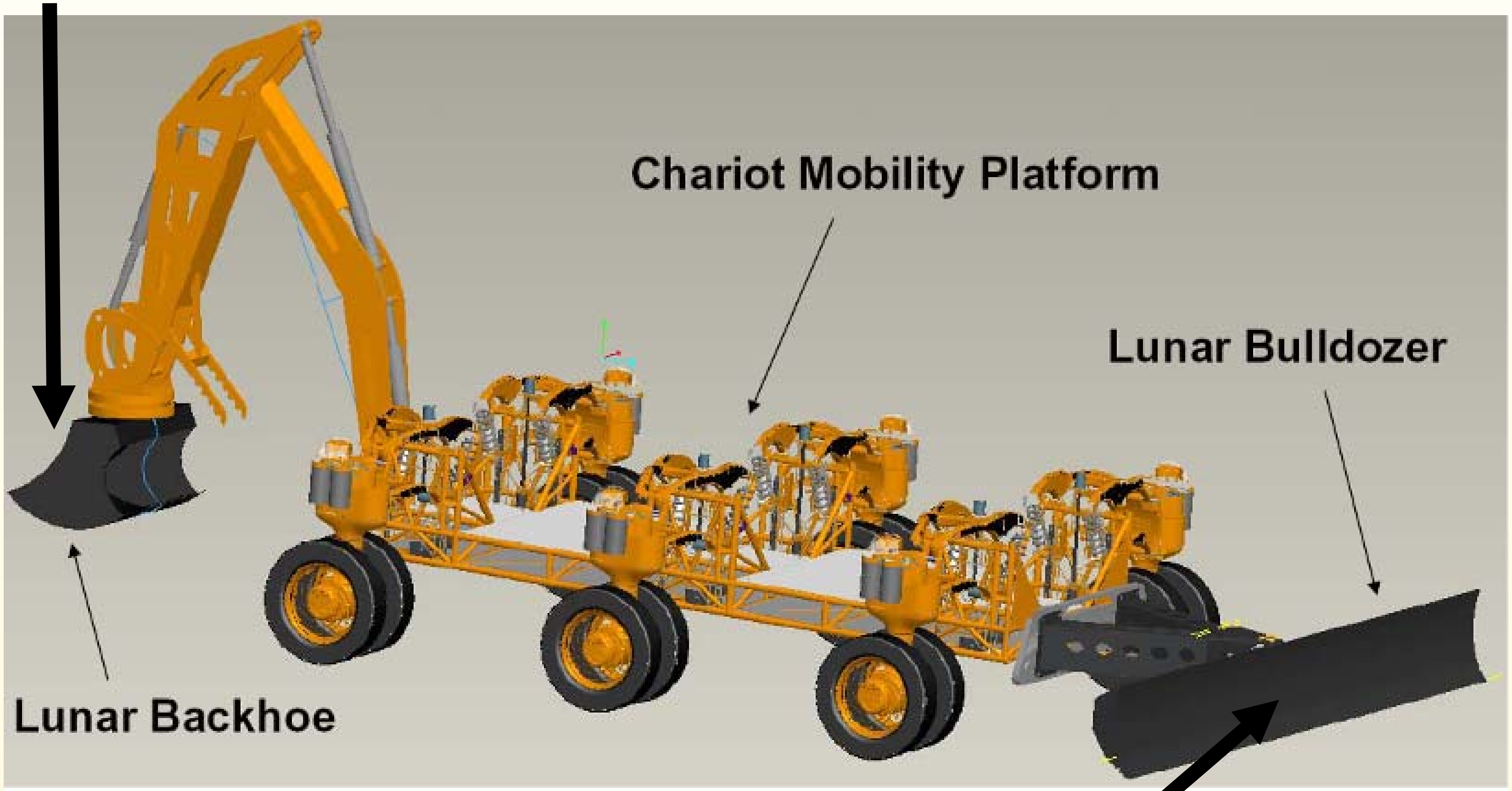
Result:

- Excavation forces reduction by 90% -> excavator mass drop from 1000 kg to 100 kg -> savings of $500 mln



Application of Percussive system on Chariot rover

Percussion can reduce vertical forces and horizontal forces



Vibration can reduce horizontal force

1. Choose a soil:

JSC-1a, GRC1, NU-LHT-1M..

JSC-1a

2. Prepare the soil:

- Relative Density, Dr = 0% - 100%
- Penetration Resistance

Dr~90%

Look at vibratory systems

3. Measure Excavation Forces

4. Scale forces for lunar G

k = 1-6

5. Use these for excavation models

Vibrating bulldozer blades, (1998)

Source of Draft force:

- Soil cutting and lifting forces
- Soil to blade friction

Parameters that matter:

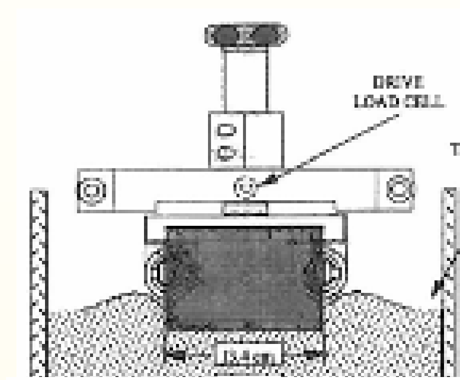
- Frequency, amplitude. direction of oscillation (best in direction of travel)

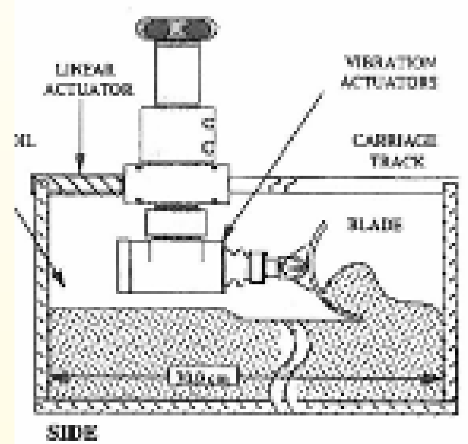
Hardware:

- Voice coil (x2):
    - Amplitude (zero to peak): 1mm at 70 Hz and 2.5mm at 10 Hz
    - Frequency: 10 to 70 Hz
    - Force: 164 N

Results:

- Highest draft force reduction for dry soils at 60-70Hz and for wet soils at 20-30Hz
- DFR ~ Bulk Density and Spec Gravity





DFR=[1-(DF Dynamic/DF Static)]*100%

71%-93%

79%-88%

87%-91%

*Szabo et al., ASAE ‘98

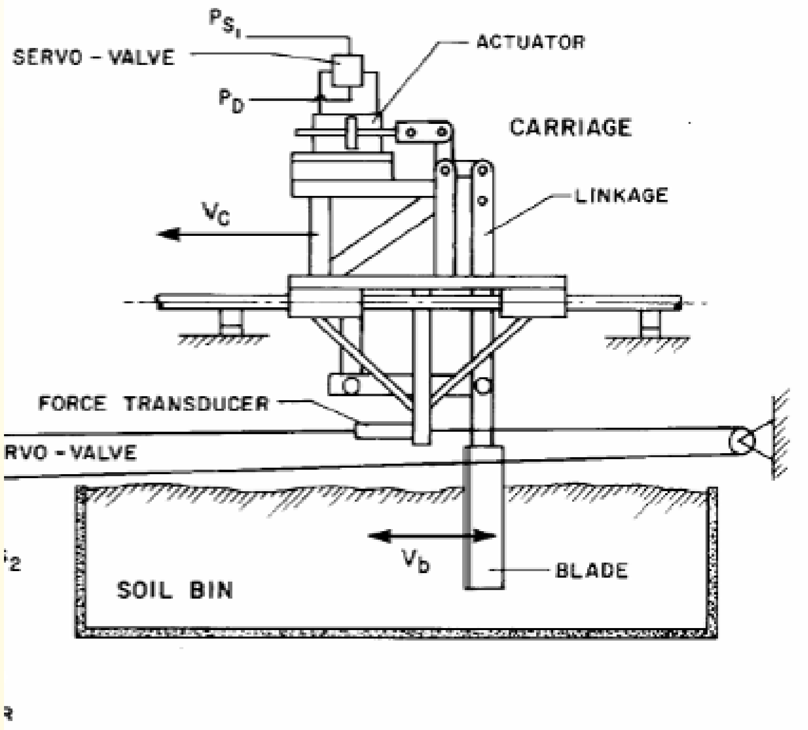
Vibratory Soil Cutting*, (1975)

- Application: cable trenching, pipe laying
- **Force reduction and Power increase:**
  - 45 deg vibrations: 60%, 1.3
  - Vertical: 50%, ~2
  - Horizontal: 40%, ~1.9
- Amplitude of Vibrations (increasing from 0.23in to 0.54in):
  - Draft Force dropped from 75 to 82%
  - Power ratio up from 1.9 to 6.4
- Frequency of Vibrations: 5 Hz to 10 Hz
  - Force reduction increase from 30% to 42%
  - Power ratio increase from 0.9 to 1.5

The percent force reduction is

$$F_r = (1 - f_r)100$$

$$f_r = F_v/F_s$$



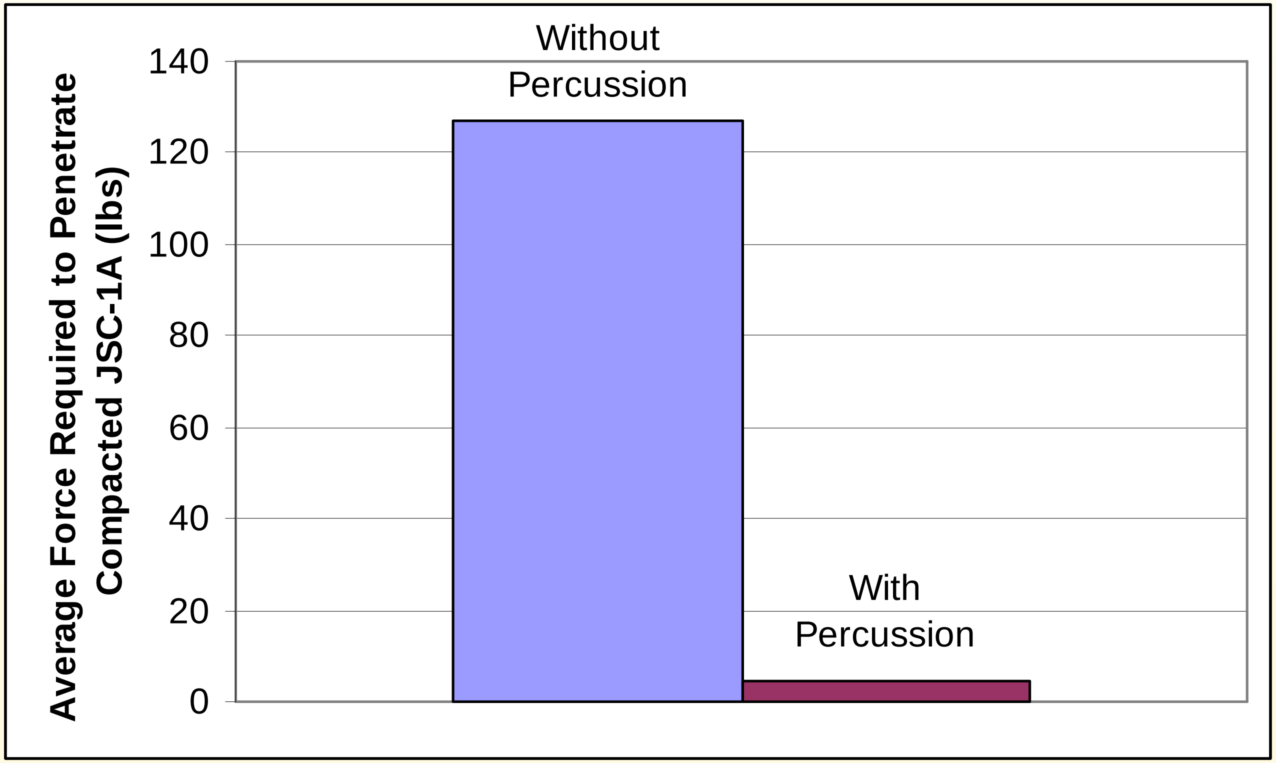
*Sulatisky and Ukrainetz, CSMT, 1975

Vibratory Soil Digging: Vertical Forces (2008)

- Estimating vertical/digging forces at Honeybee Robotics
- Soil: JSC-1a at ~1.9g/cc
- Without percussion: 125 lbs (but could not push the scoop all the way in)
- With percussion: 5 lbs

Percussive actuator

Scoop



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Department of Defense systems

Challenge:

- Man-transportable (~30 kg), rover-based digging systems can be used to uncover buried Improvised Explosive Devices
- Light platform => Limited reaction force => Limited digging capability

Solution:

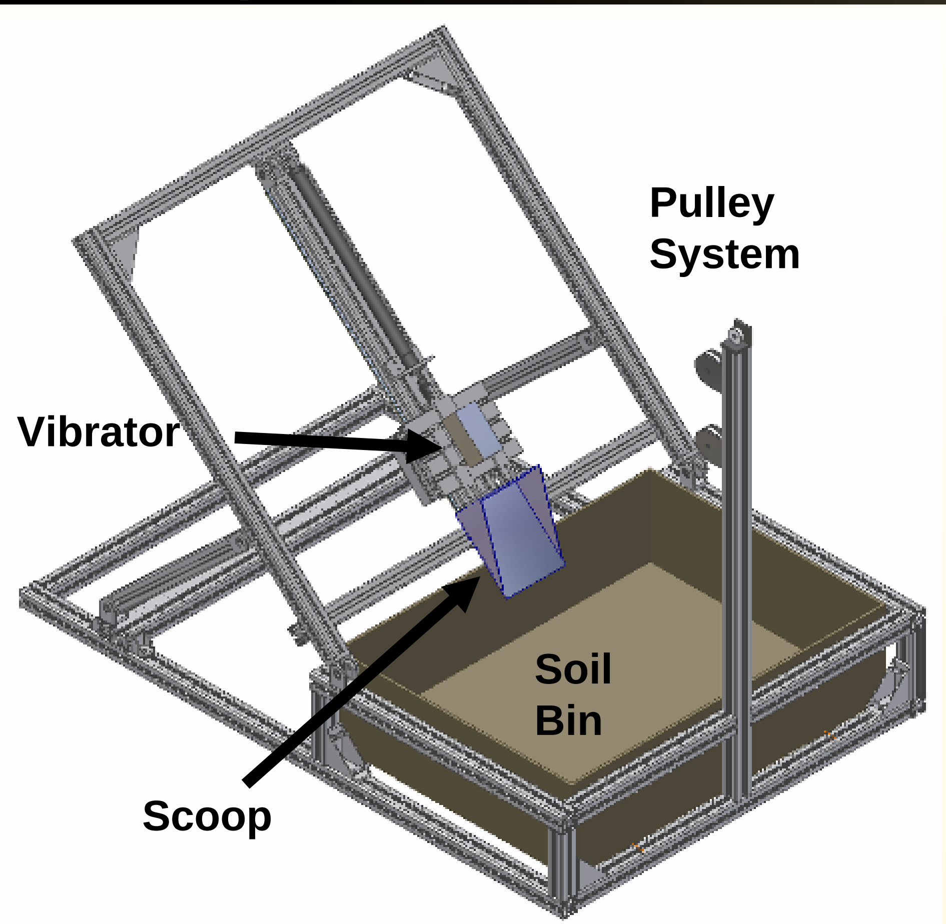
Percussion/Vibration enhanced digging greatly improves digging capability

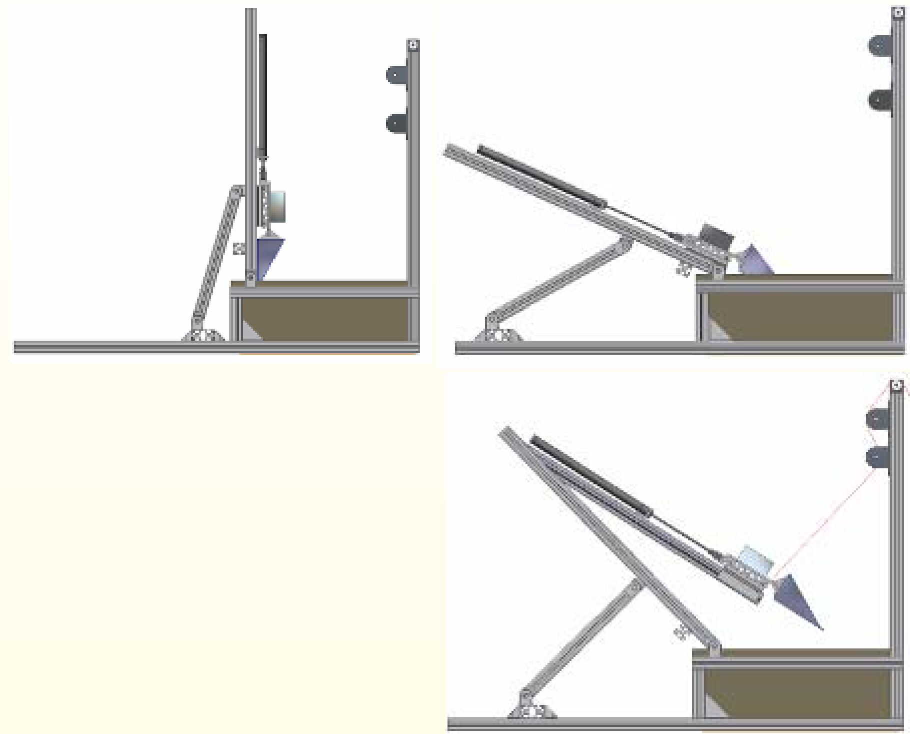
Foster-Miller: Talon

iRobot: PackBot

Experimental evaluation of percussive technology for digging and scooping (not bulldozing)

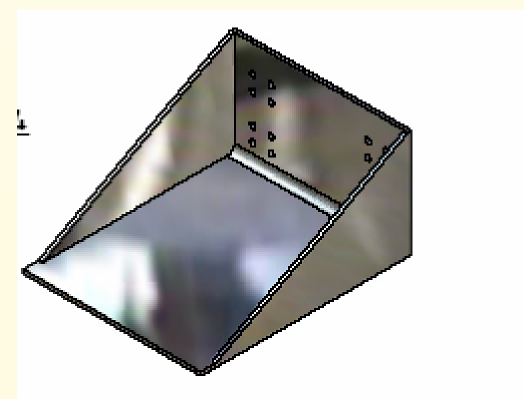
Components of the test fixture





Scoop Capacity

- Volume: 1500 cc
- Mass: ~ 1.5 kg (assume 1g/cc)



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Actual Set up

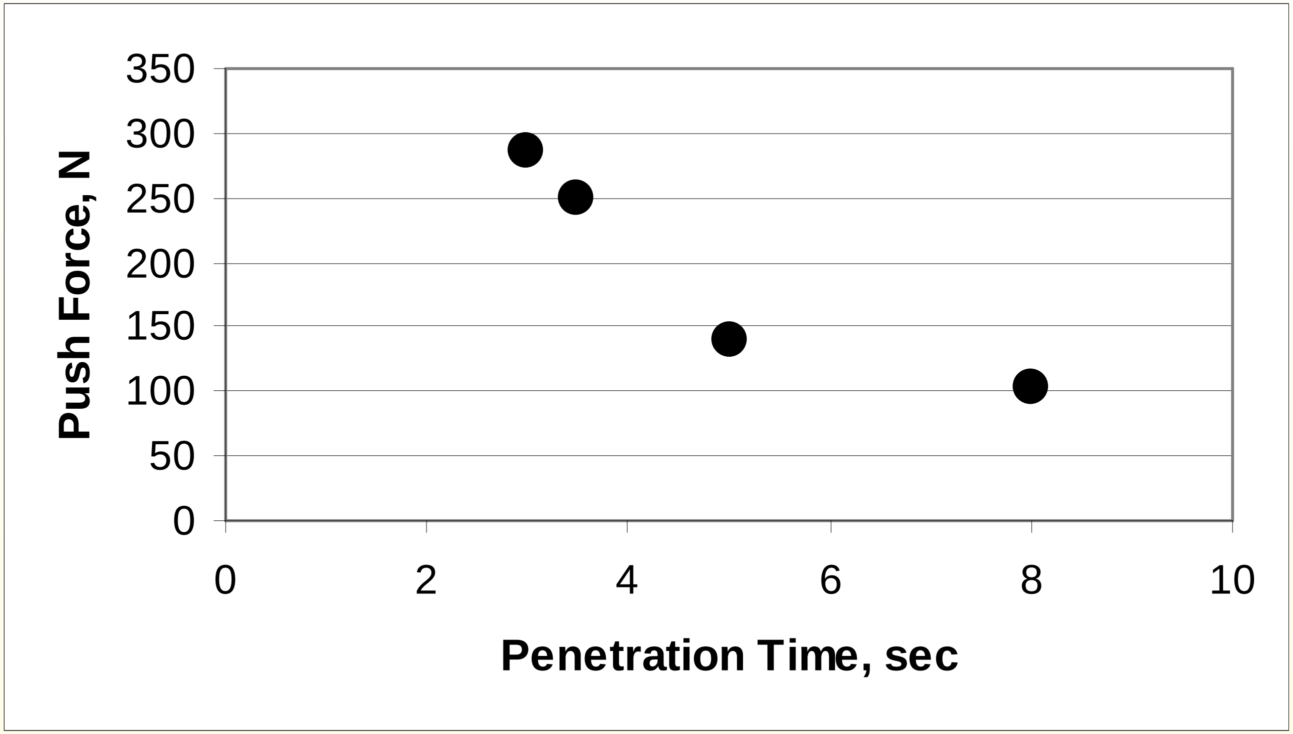
- JSC-1A compacted to 1.9 g/cc
- Could not push the scoop into the regolith (physically impossible)!!!
- Percussive hammer: 2.6 J/blow, 66Hz, 170 Watt

Quality control: 3.7 MPa (Apollo: 0.5-1.7 MPa @ 70cm depth

Movie time

Results and Analysis

Higher push force->faster the scoop penetrates.



Quick Analysis

- Assume: Excavation requirement: 4500 m3 or 3,000,000 scoops
- **Digging**
  - 420 kWhr for 300 N push force
- **Extracting/lifting the scoop**
  - 140 kWhr for 300 N pull force
- **Total Energy Requirements (Digging and scooping up):**
  - 560 kWh for 300 N digging force

There is a trade off between excavation force (excavator mass) and digging power

consider this:

- 1kg of excavator mass = $100k (launch cost)
- Power can be solar (‘free’)

1. Choose a soil:

JSC-1a, GRC1, NU-LHT-1M..

JSC-1a

2. Prepare the soil:

- Relative Density, Dr = 0% - 100%
- Penetration Resistance

Dr~90%

3. Measure Excavation Forces

Vibratory & Static

4. Scale forces for lunar G

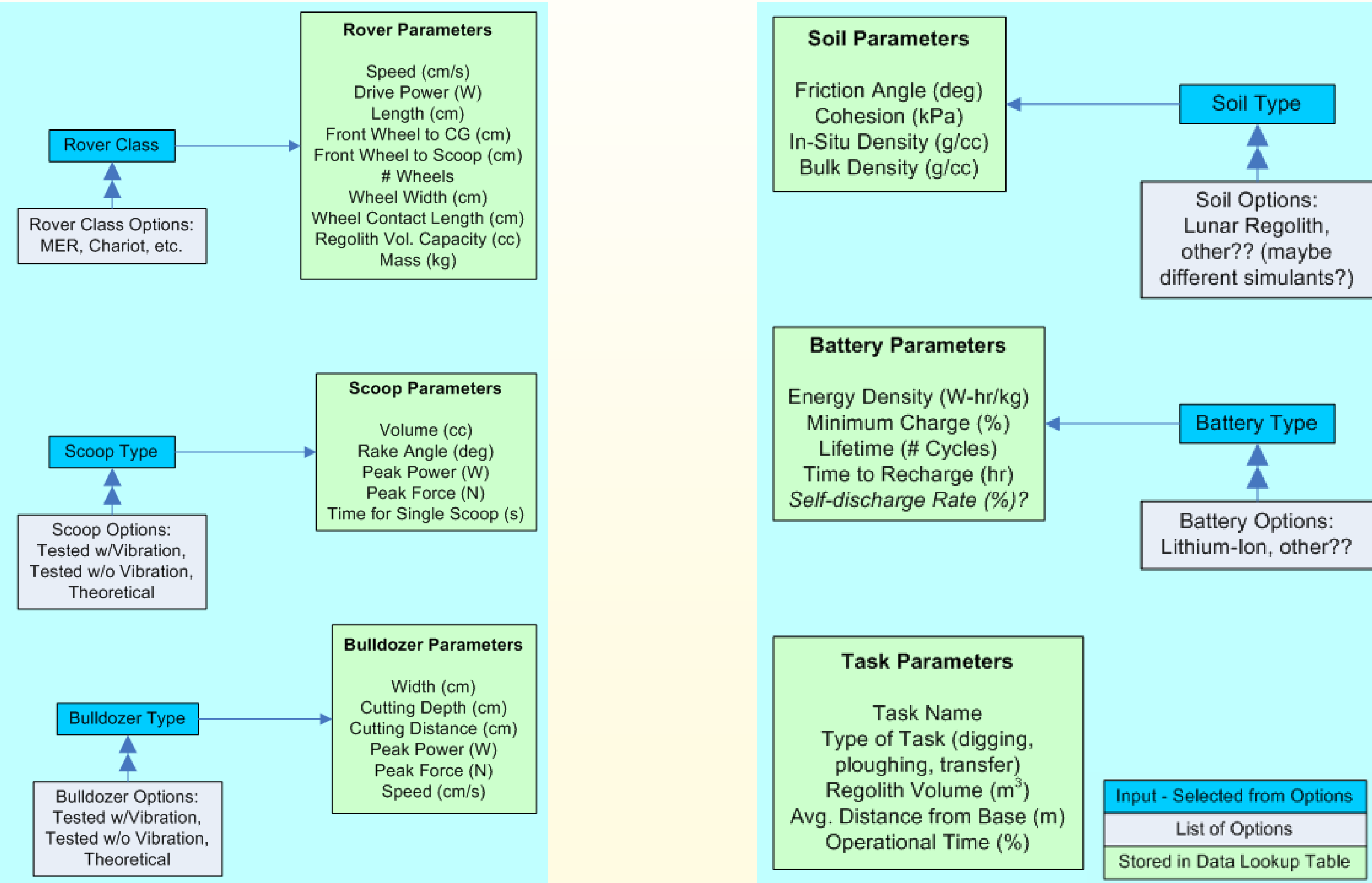
k = 1-6

5. Use these for excavation models

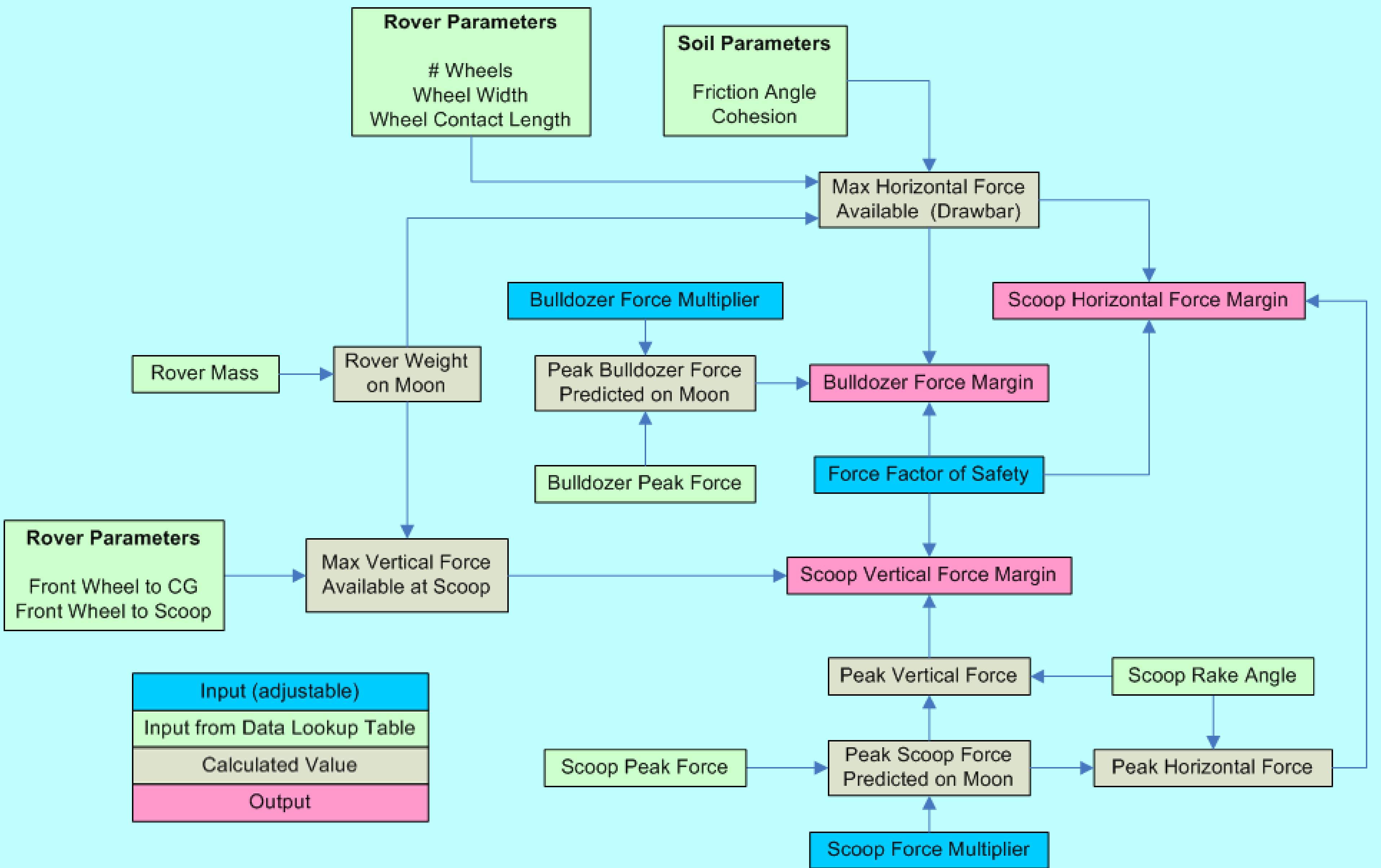
Excavation Spreadsheet

- Compiled parametric spreadsheet for assessing various excavation tasks.
- Clearly defined and separated inputs and outputs
- Clearly defined excavation tasks
- Modular design allows input of additional parameters or constants

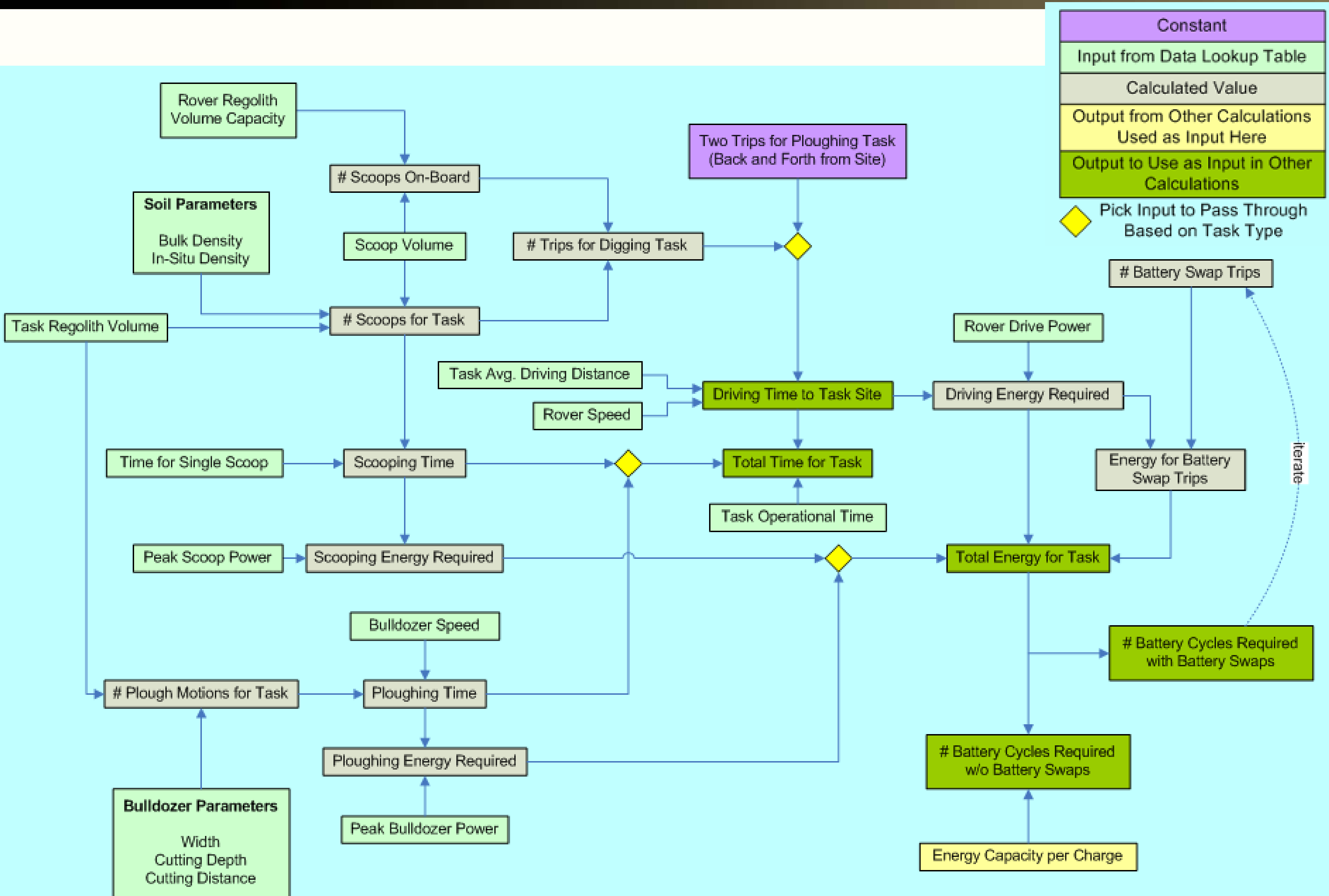
Parameters for Fixed Data Input Table



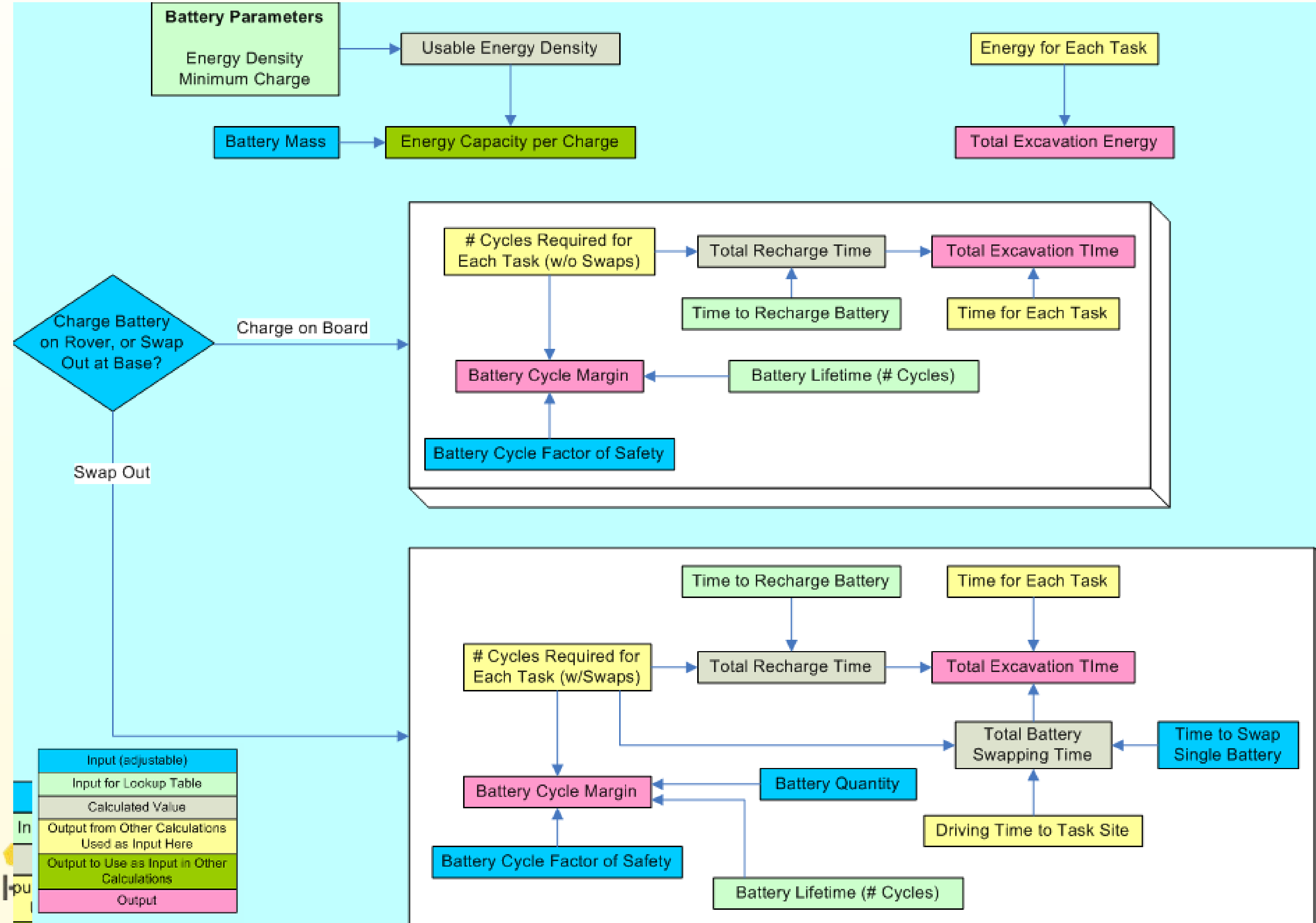
Force Calculations and Margins



Calculations for Each Excavation Task



Time and Energy Calculations



Actual Spreadsheet

Case study: digging cable trenches

Details	Units	No Percussion	With Percussion
Regolith Volume	m^3	75	75
Avg. Distance from Base	m	140	140
Operational Time	%	50	50
# Scoops for Task	#	86695	86695
# Trips for Task	#	130	130
Scooping Time	hr	349	349
Driving Time	hr	2	2
Total Time for Task (no swaps)	hr	702	702
Scooping Energy	**kW-hr**	**0.0**	**59.4**
Driving Energy	kW-hr	0.90	0.91
Total Energy for Task (no swaps)	kW-hr	0.9	60.3
# Battery Cycles for Task (no swaps)	#	1	54
Peak Horizontal Scoop Force (Moon)	N	1915	113
Peak Vertical Scoop Force (Moon)	N	1607	80
Excavator Mass (based on horizonta	**kg**	**3000**	**200**

energy

mass

The mass of batteries holding 60 kWhr of energy is 800 kg. Thus, if a 200kg excavator required its own power supply, the total mass would be 1000 kg. This is 2000 kg less than the excavator that does not use percussive system.

HONEYBEE ROBOTICS

Let’s look at 4 steps of excavation process

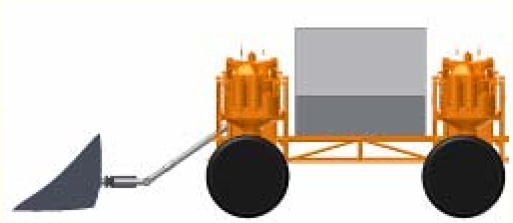
Excavation 4 Steps

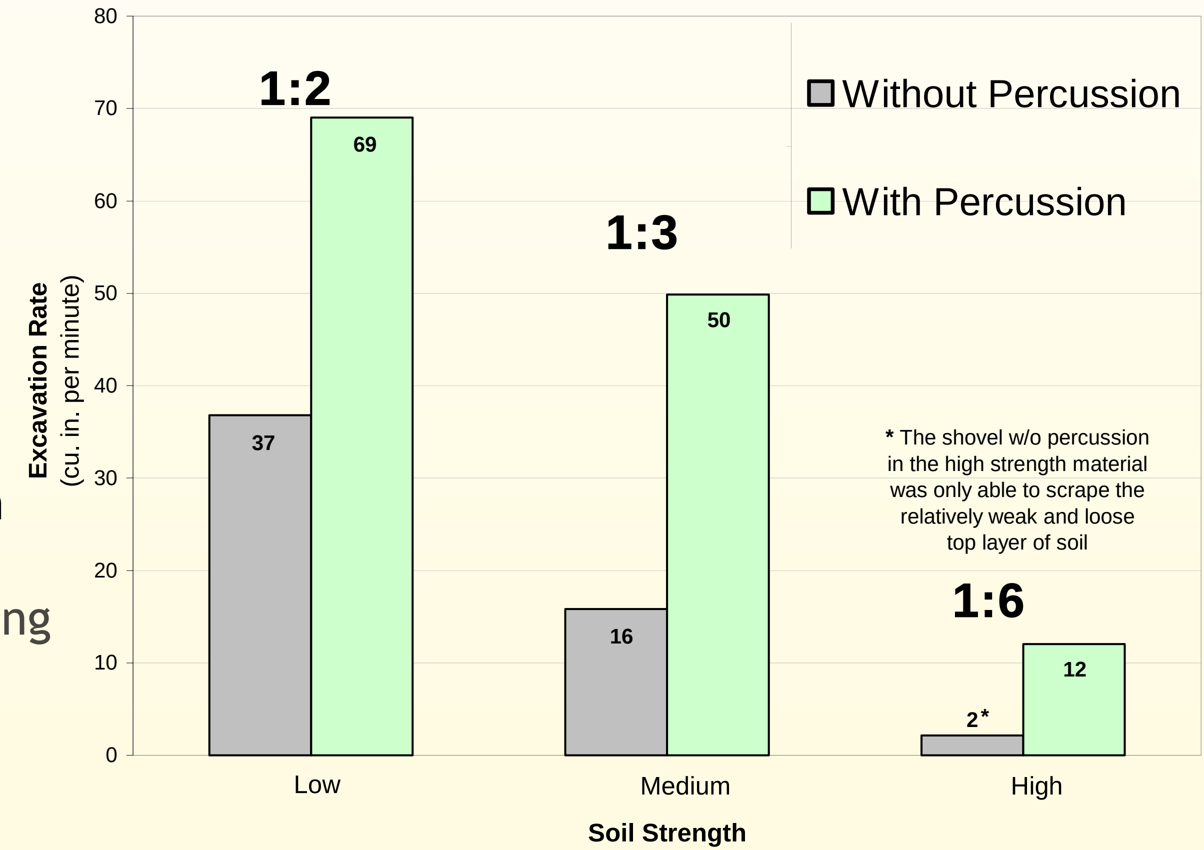
The entire excavation cycle is a sequence of 4 steps:

1) dig and scoop, 4 sec
2) move over the mining container
3) discharge
4) move back into the regolith

1, 3: time saved with percussion

2,4: power/time wasted in moving regolith. Alternatives?



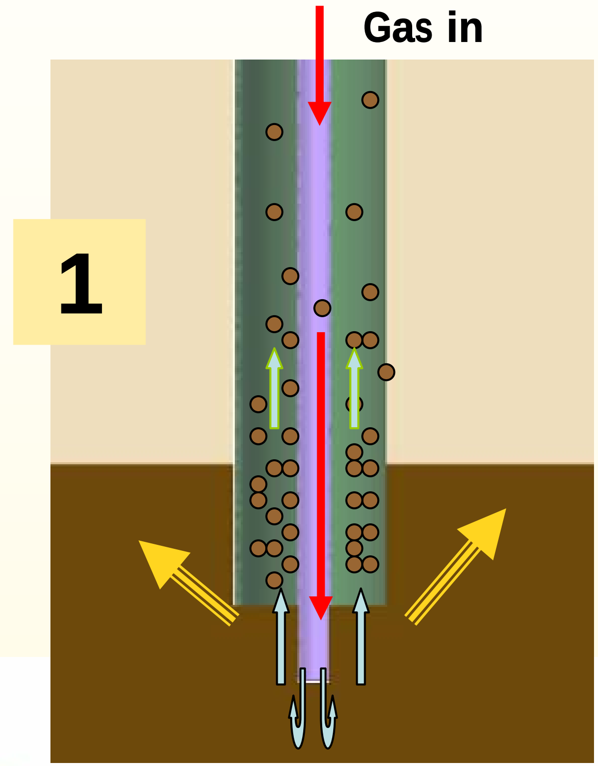


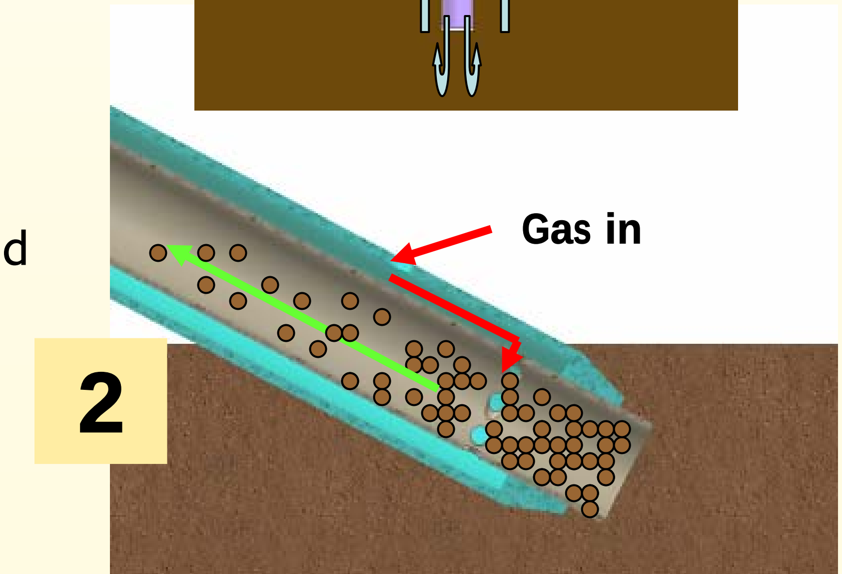
HONEYBEE ROBOTICS

Pneumatic Excavator and Transfer

- **Principle of operation:**
  1. Gas is injected into regolith and as it escapes it exchanges momentum with soil particles lifting them up
  2. Regolith trapped inside a tube is lifted by injected gas

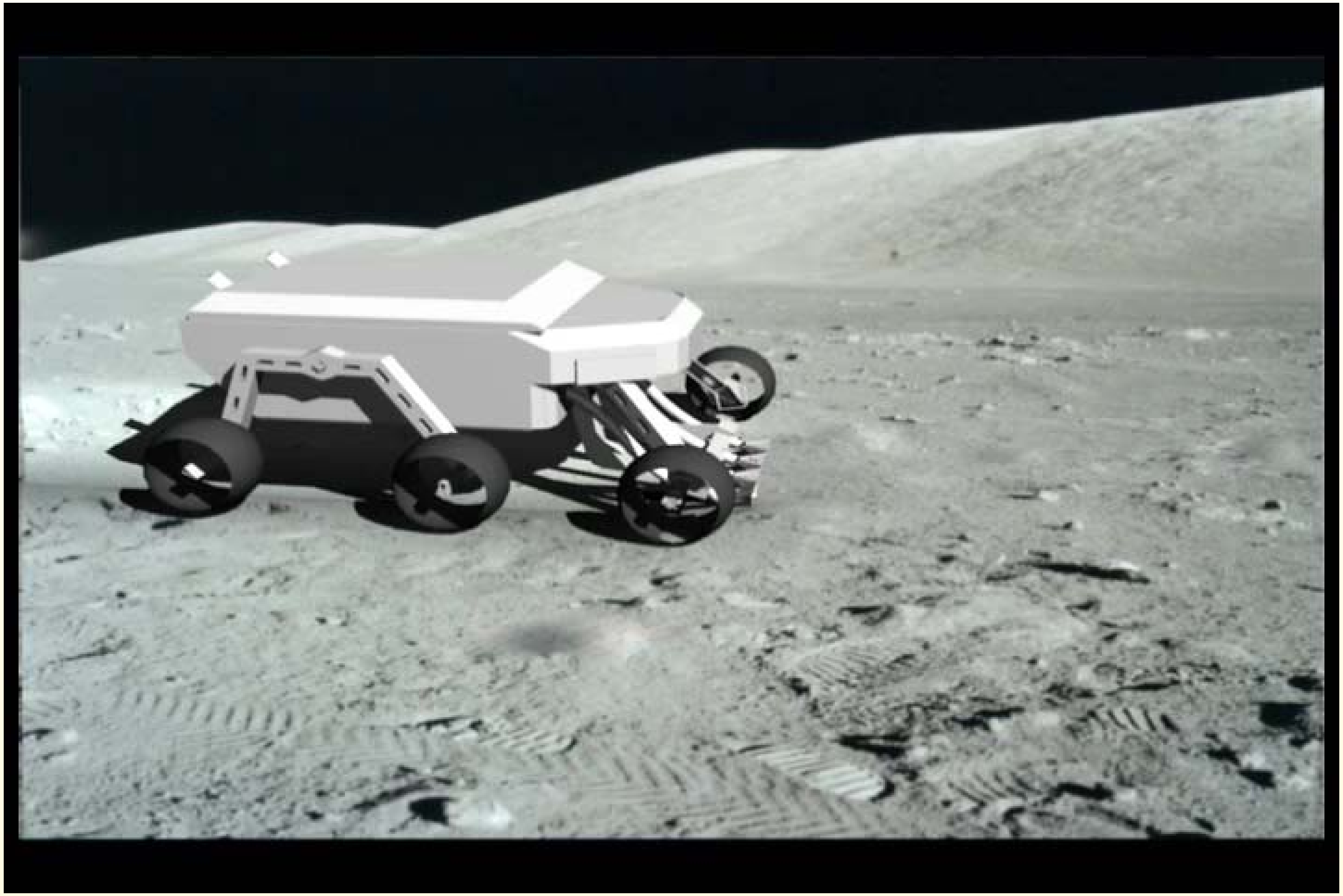
- **Gas sources:**
  - Propulsion pressurizer gas: Helium
  - By-product of ISRU gases
  - Burn residual propellant in a thruster and use exhaust gas





HONEYBEE ROBOTICS

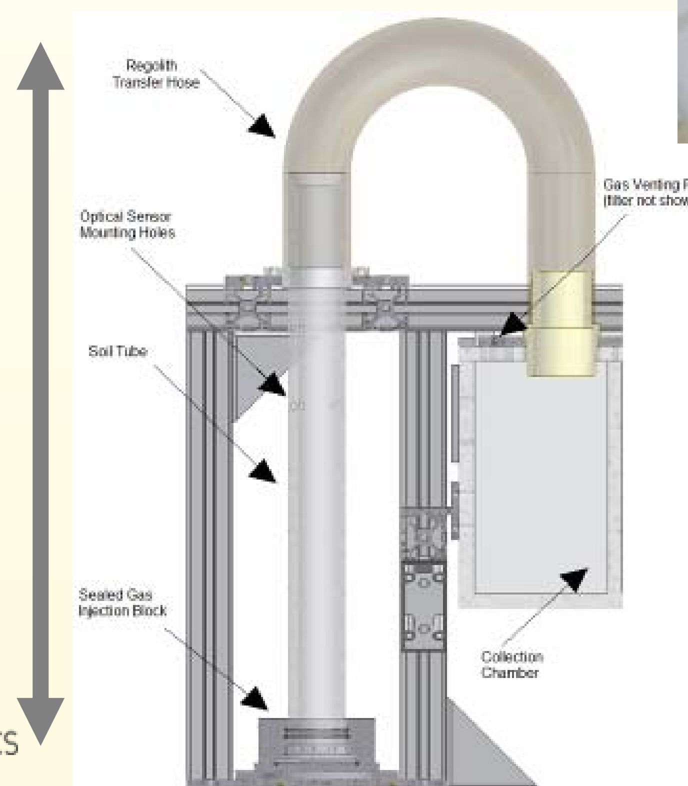
Percussive-Pneumatic Excavator

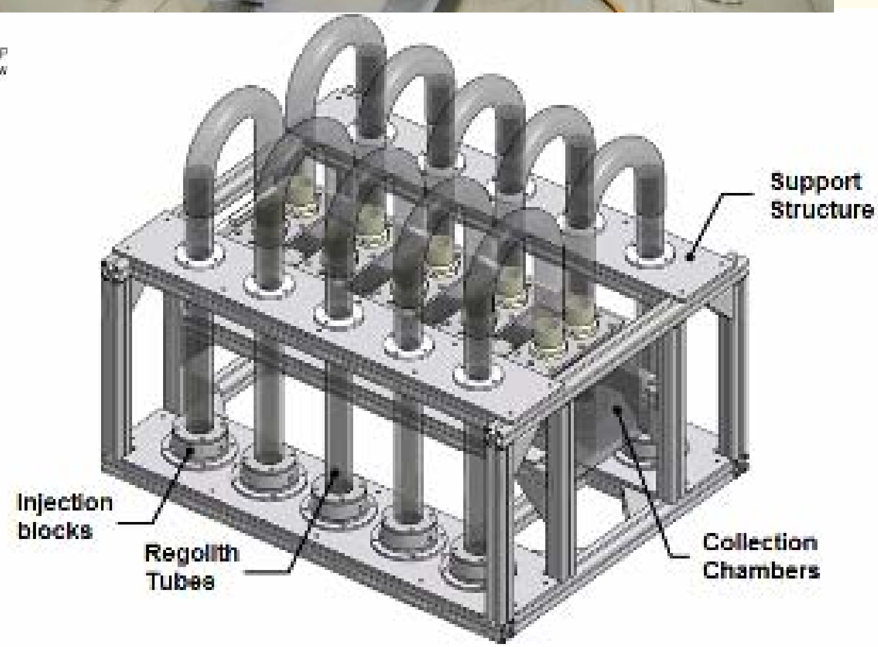


Tests at Lunar G and in Vacuum

- **Gas: Nitrogen @ < 9 psia**
- **Initial Soil Mass: 50g or 100 g**
- **Material: JSC1-a**
- **Chamber Pressure: ~ 1-4 torr**
- **Gravity: 1.67 and 9.8 m/s^2**

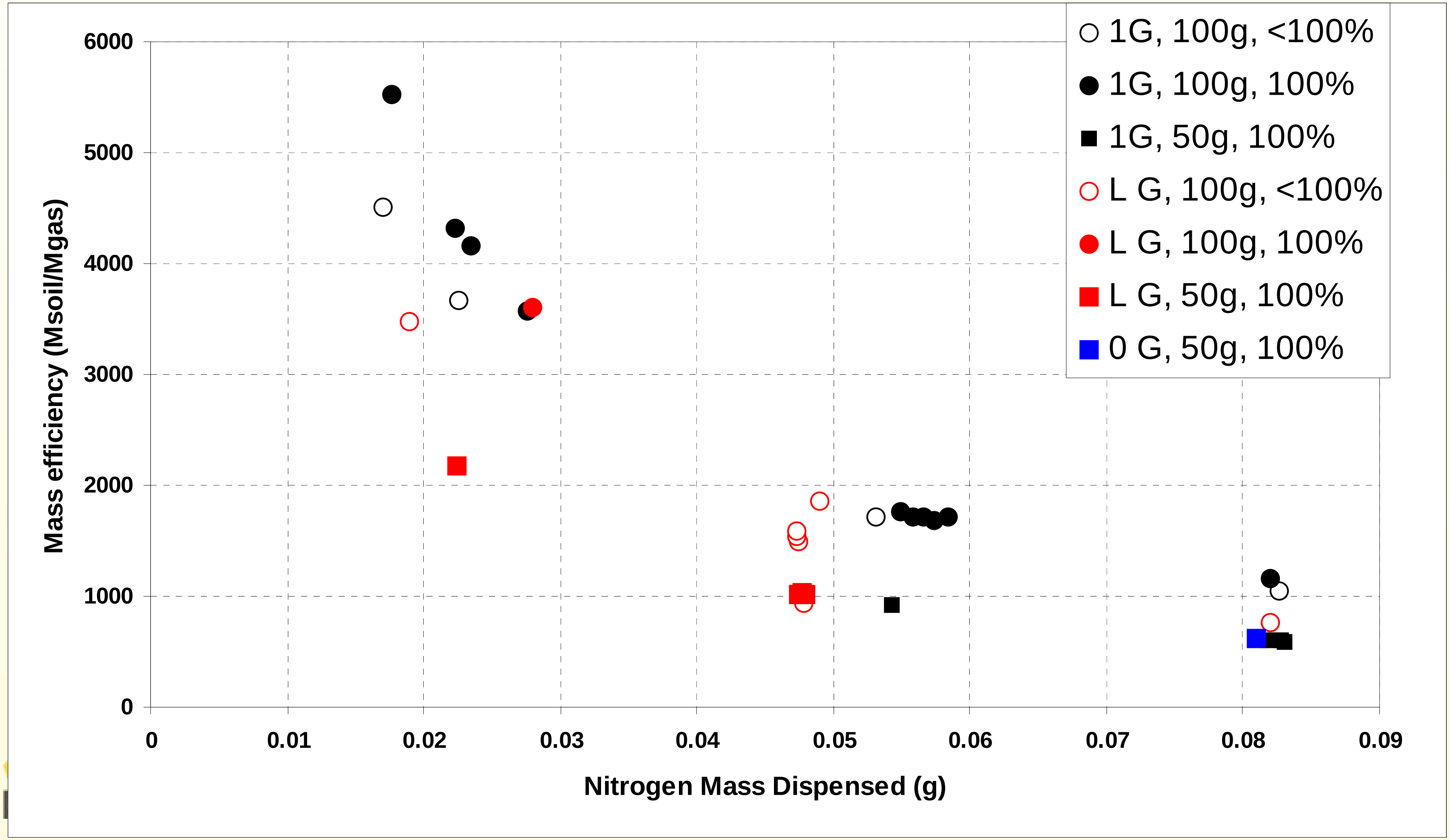
2 Feet





Test Results:

- 1 gram of N_2 at 7 psia can lift over 6000 g of JSC-1a
- In Hard Vacuum efficiency of 1:10 000 possible

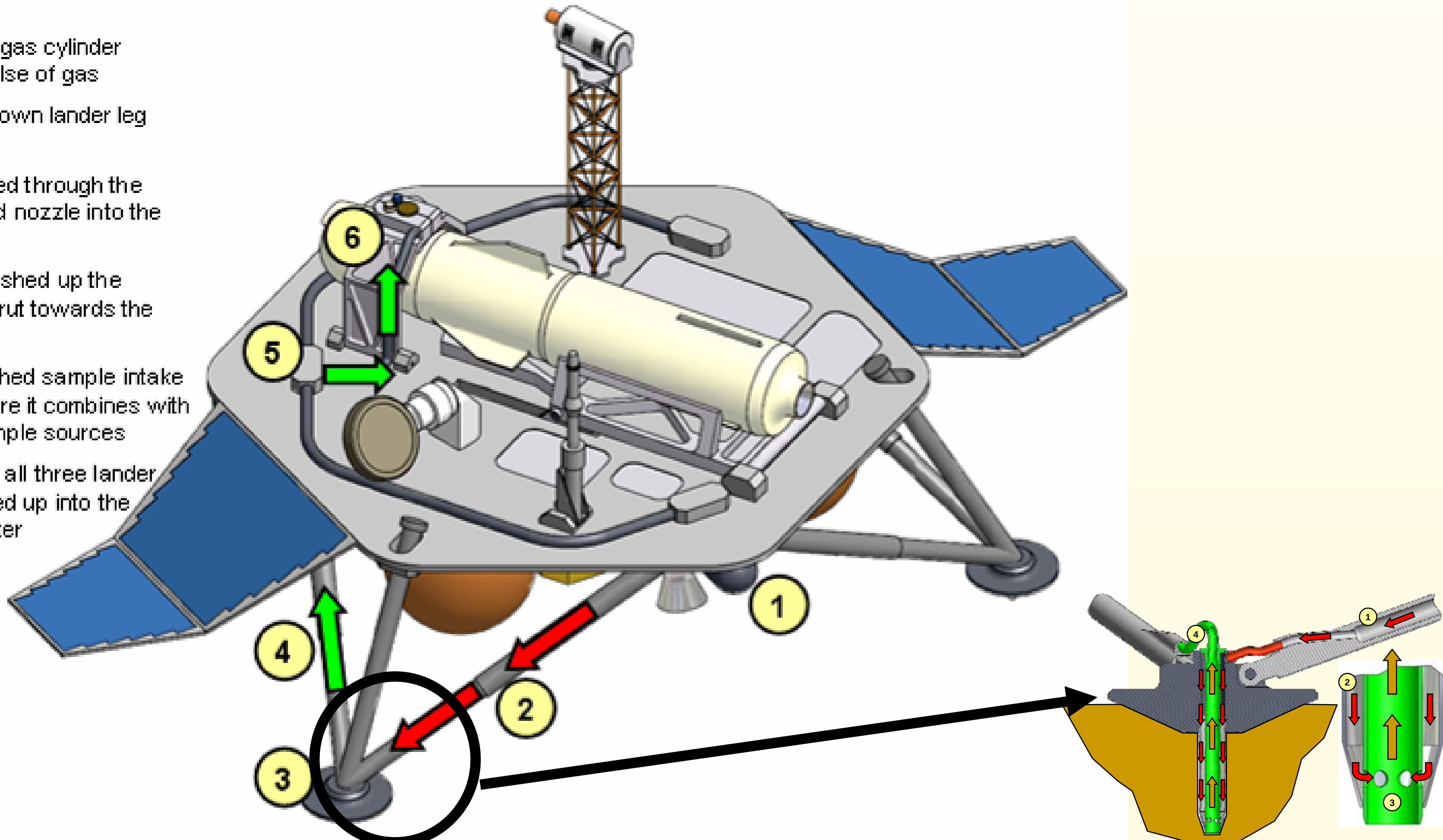


Pneumatic Sampling

Pneumatic sampling tube can be embedded inside each leg of a lander for either:

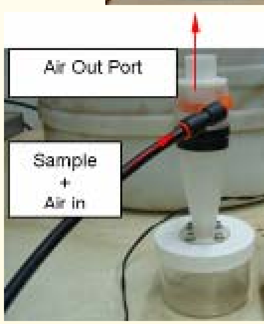
- Sample return or
- Reconnaissance: hop from place to place and acquire soil for analysis in the lab

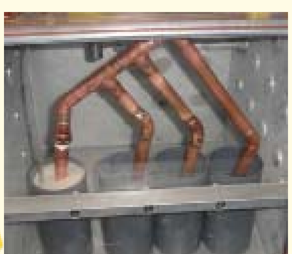
1. Compressed gas cylinder releases a pulse of gas
2. Gas travels down lander leg strut
3. Gas is expelled through the lander leg pad nozzle into the regolith
4. Regolith is pushed up the second leg strut towards the lander deck
5. Regolith reached sample intake manifold where it combines with two other sample sources
6. Regolith from all three lander pads is pushed up into the sample canister



Particle separation for ISRU

Particle Separation “Dry” Methods





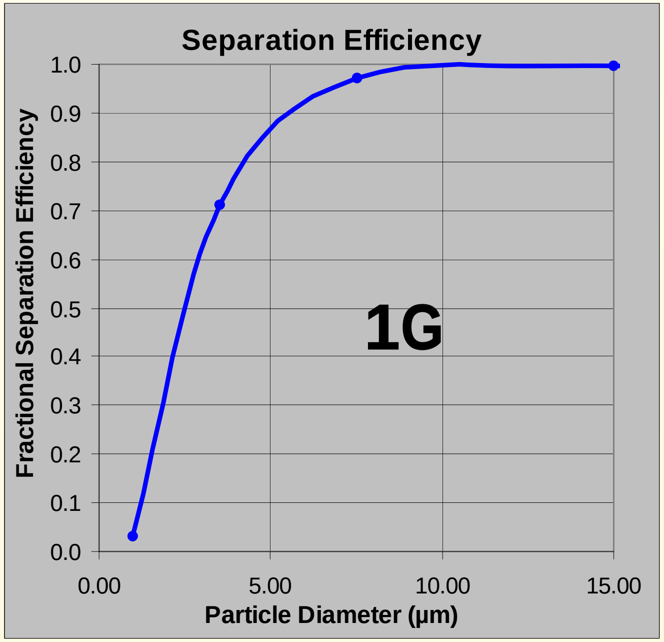
Method	Advantageous	Disadvantageous
Sieve	1. Simple 2. No moving parts	1. Sieve WILL get blocked 2. Electrostatics is an issue 3. Need vibrations (e.g. piezo) - additional electrical component
Cyclone	1. Robust 2. Gas can be recycled	1. Needs gas carrier 2. “Cut-off” not very sharp 3. Needs testing to determine optimum dimensions
“Bag Pipes”	1. Robust 2. Gas can be recycled	1. Needs gas carrier 2. “Cut-of” not very sharp 3. Needs testing to determine optimum dimensions

HONEYBEEROBOTICS

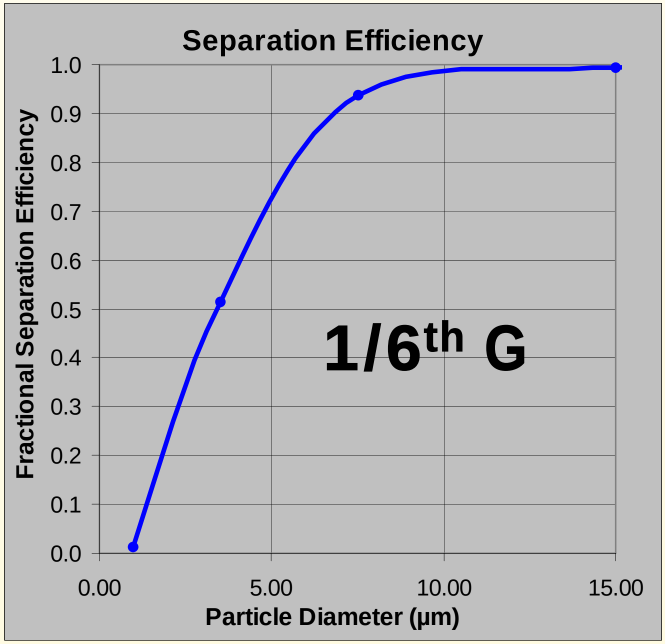
Cyclones

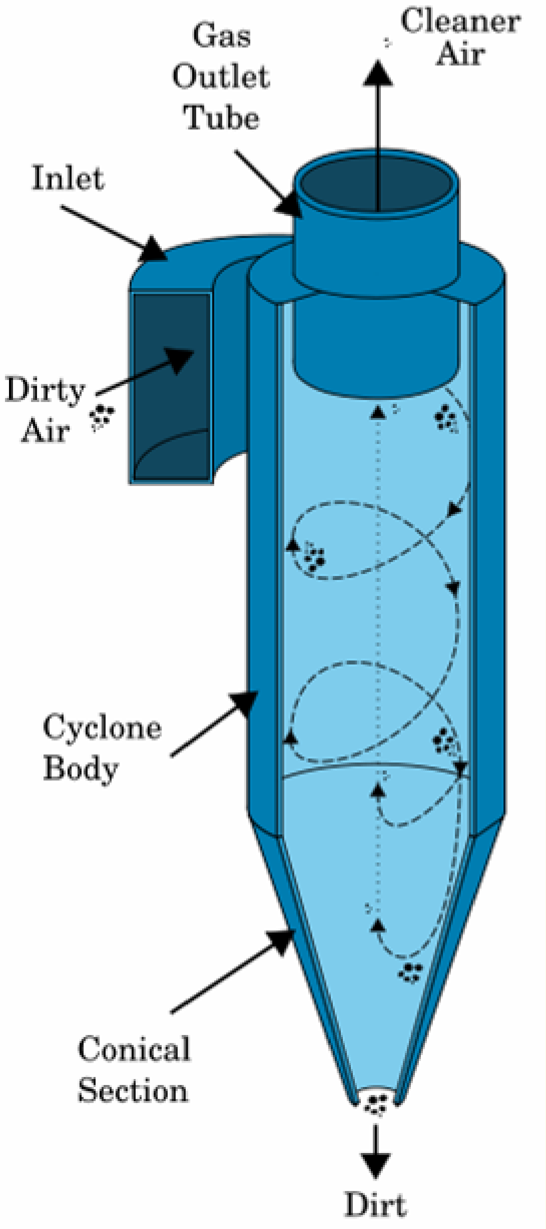
- Cyclones theory is well established
- Many very complicated equations exist to determine cut-off between coarse and fines
- High efficiency cyclone captures ALL particles
- Can use double stage cyclones
- Our goal is to have ‘inefficient’ cyclone:
    - capture fines and leave out coarse

All particles >8 micron will settle



All particles >11 micron will settle





“Bag Pipes”: 2 stage process

Actual set up inside a vacuum chamber

Step 2:

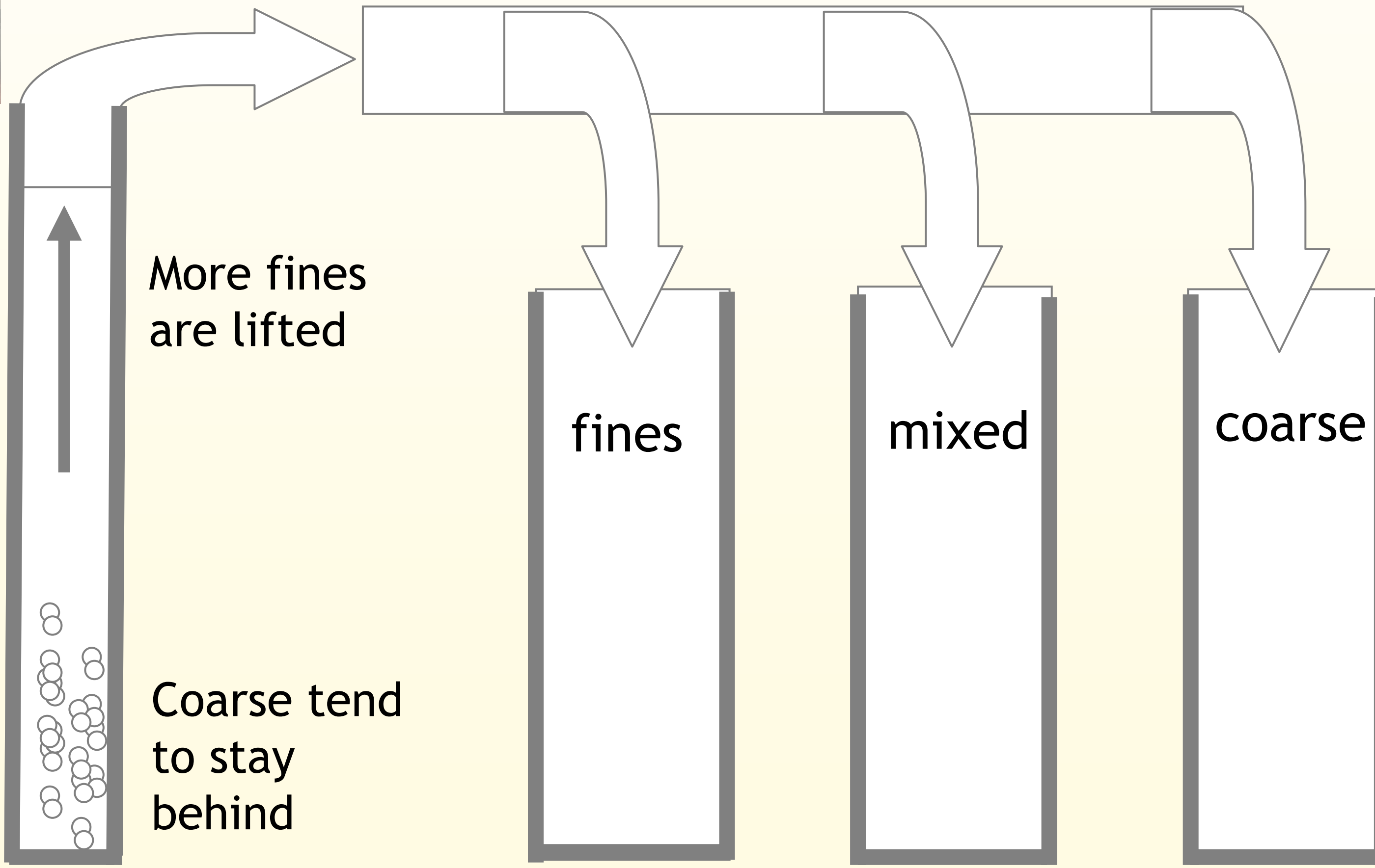
Fines follow gas flow and ‘turn’ corner

Coarse travel further

Step 1:

Fines are preferentially lifted

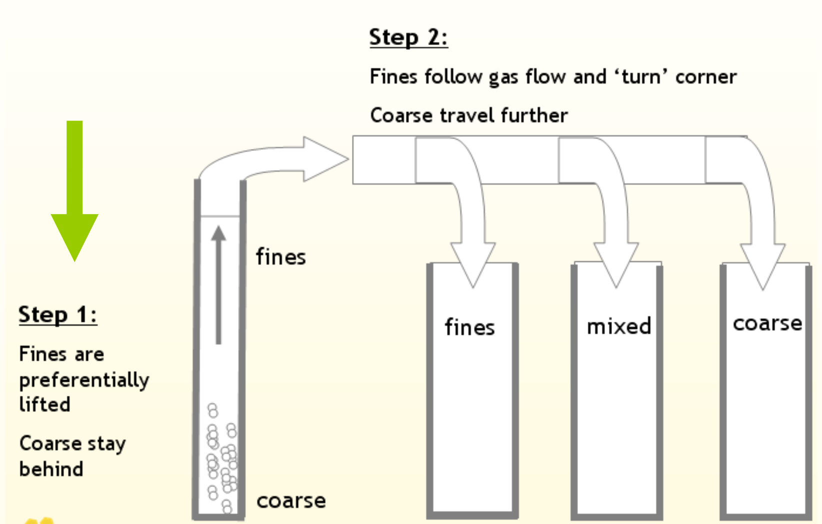
Coarse stay behind

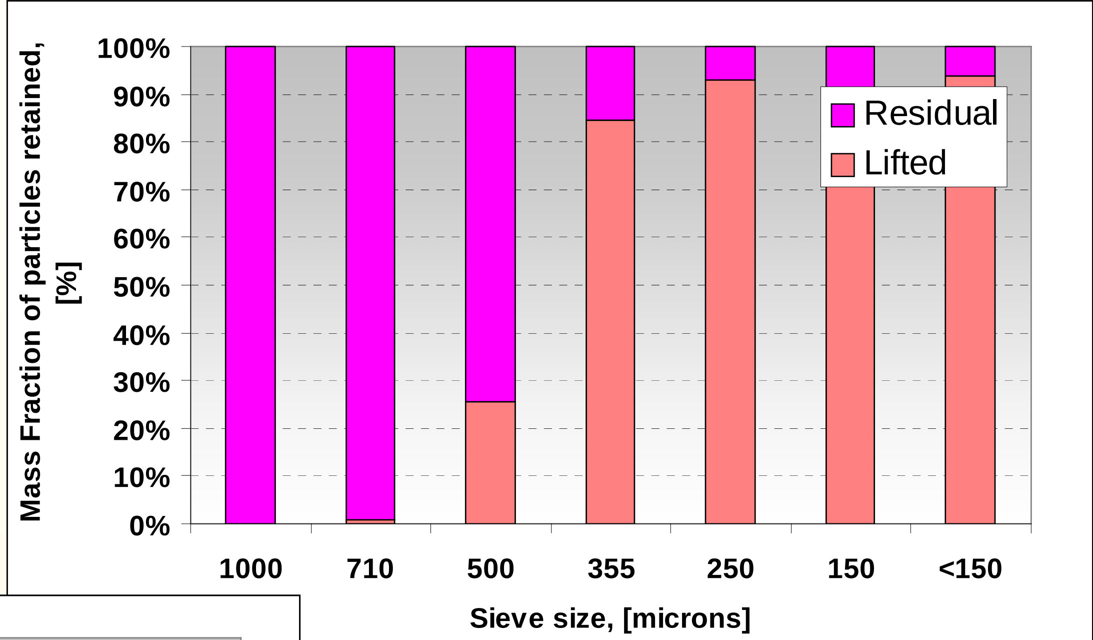


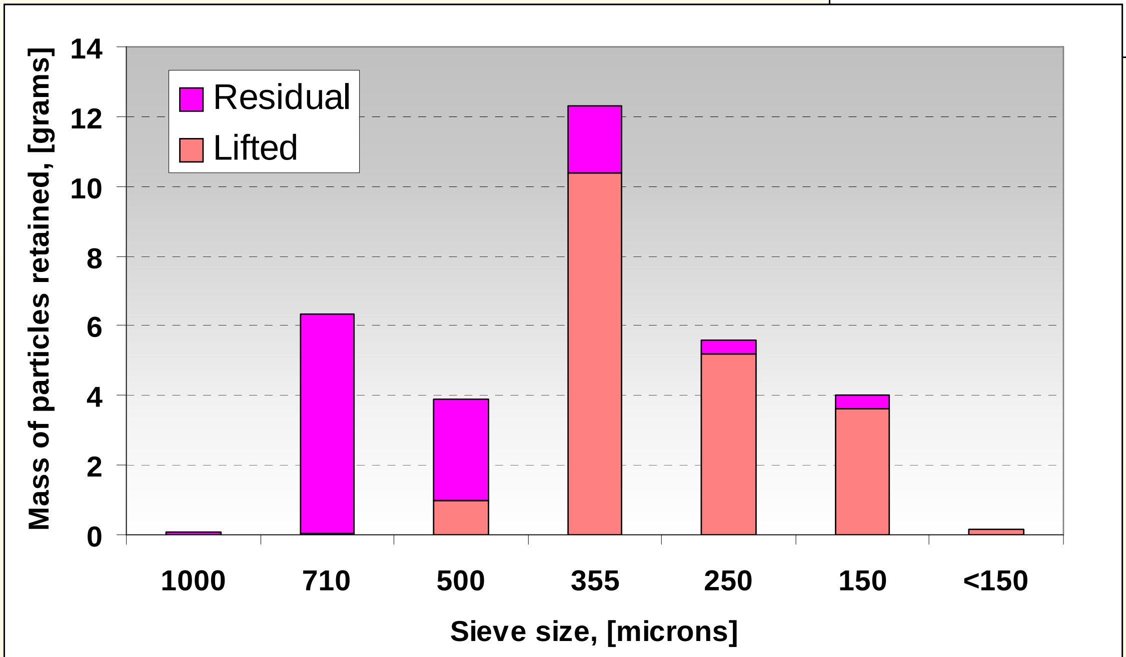
Gas injection point

cs

"Bag Pipes": 1st step



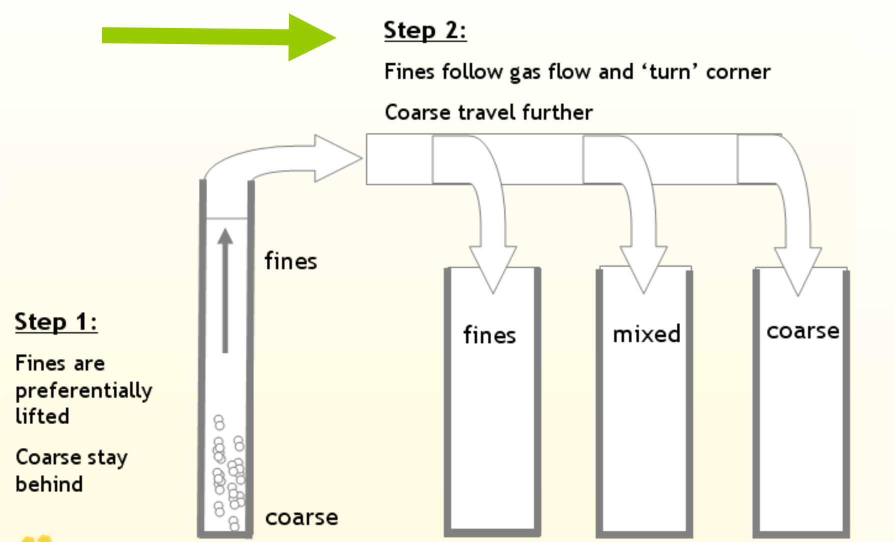


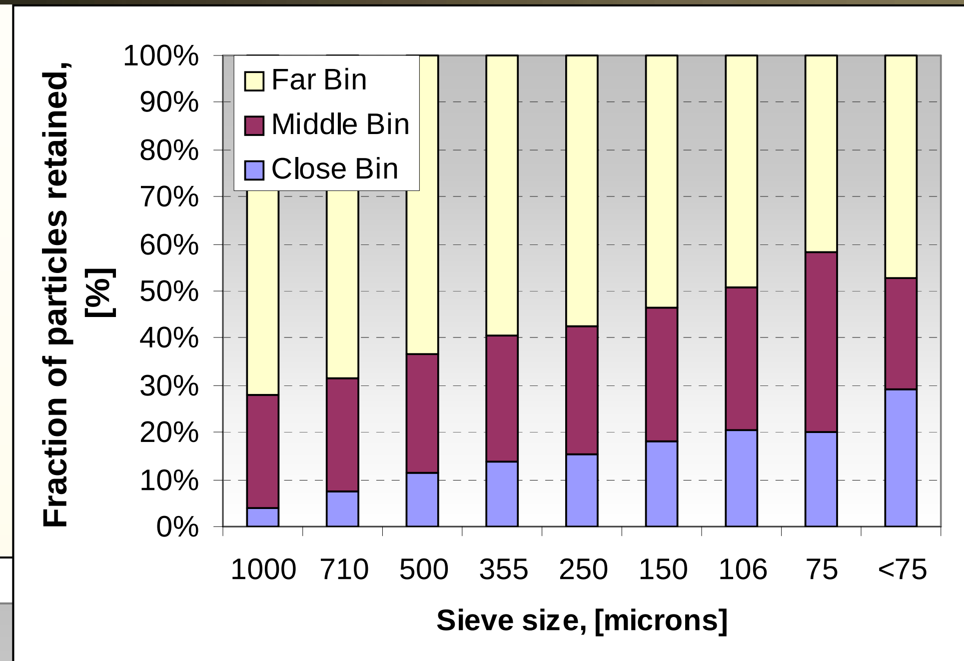


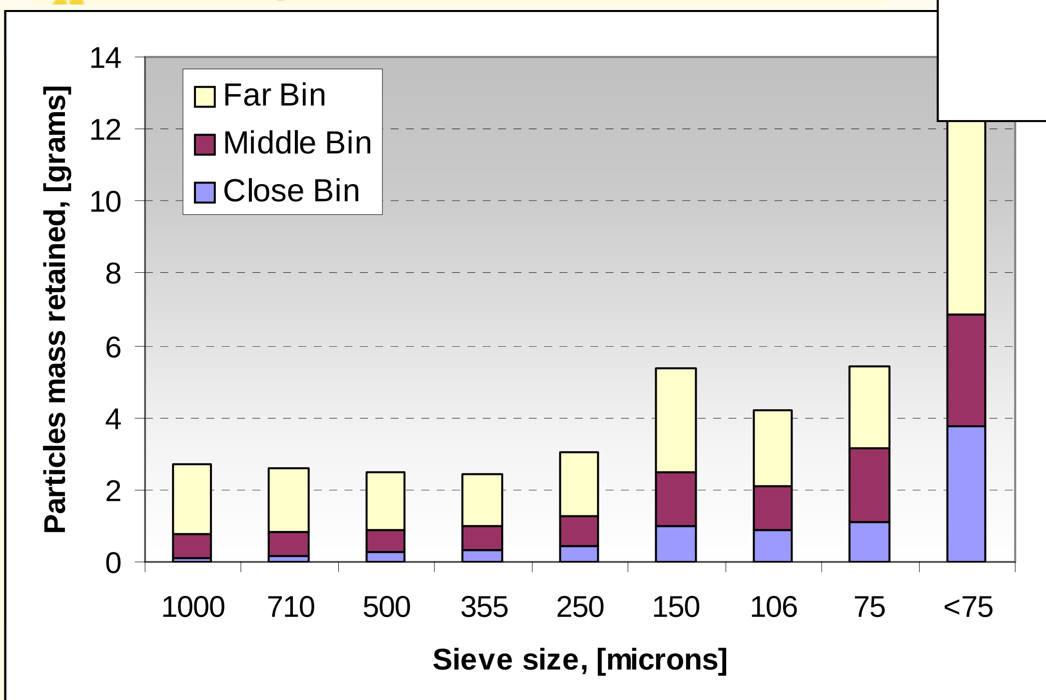
Results:

- Particles lifted out of the tube tend to be finer
- Results depend on a number of parameters

"Bag Pipes": 2nd step







Results:

- Closest bin collects mostly fines
- Furthest bin collects mostly coarse
- Results depend on a number of parameters

Path Forward

1. Develop prototype hardware for excavation tests
2. Test, test, and test some more
3. Address gravity scaling by testing at 1/6 and 1 g
4. Refining excavation models
5. Develop operational scenarios

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